Existing Buildings as Material Banks

Material Passport´s Suitability Towards the Existing Building Stock

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Synopsis:

This thesis researches how material passports and guidelines for reusing materials fits with existing building stock. The student outlines a problem field where the built environment contributes with environmental-friendly innovations and solutions with harvesting time post hoc some of the most agreed-upon global sustainability goals. Thus, if the built environment shall contrive to sustainability goals due 2030-50, several researchers argue towards a circular preservation of embodied energy and how material banks from existing buildings for reuse purposes is a part of this solution.
This thesis firstly investigates how existing best practices of material passports fits its purpose towards existing buildings. The research is carried out by a mixed method, combining an initial analysis and a survey to form the discussion. The initial analysis conducts a literature review upon existing technology and theories, while the survey investigates designer's thoughts on mapping an existing building with the purpose reusing materials. From the survey-results, the student forms a recommendation for further proceedings for including existing buildings into circular thinking in a more efficient manner.

Preface

This master thesis marks the end of my five years as a student within the built environment, finishing my degree in *Management in the Building Industry*, a Master of Science (M.Sc). It is been a wholesome and incredible experience, both the three years at the Norwegian University of Science and Technology in Trondheim, and the final two years at Aalborg University. I would like to send my warmest regards to all student colleagues and friends that have been a part of this journey. It is wistfully to end this journey, but with increased knowledge, experience, and curiosity, I am pleased to finally step into the real world of construction.

For this thesis, I would like to thank my supervisors Kjeld Svidt and Ekaterina A. Petrova for valuable guidance throughout the semester. Also, a big thank you to all the survey-respondents out in the industry who contributed to this thesis.

Finally, the biggest thank you and appreciation to my mom Lisbet, dad Morten and older brother Øystein for being supportive, tolerant and always resourceful through my years as a student, especially in the times when it was needed the most.

Erling Vånge

Reader´s Guideline

The structure of this thesis is given in the following table:

Name	Description
Chapter 1 Introduction	Presents thematically background, problem field and initial hypothesis
Chapter 2 Scientific Research Methodology	Presents research method and design, reliability and validity and the thesis´s limitations
Chapter 3 Initial Analysis	Presents the theoretical framework
Chapter 4 problem Statement	Present the Problem Statement
Chapter 5 Data collection	Illustrates and explains the creation of the survey used to collect primary data
Chapter 6 Results and analysis	Analyse, validate and presents the results from the survey
Chapter 7 Discussion	Presents the findings from the analysis and discusses its meaning in correlation with relevant theory.
Chapter 8 Suggested Solution	The students suggested solution upon the problem statement realized with the arguments from the discussion.
Chapter 9 Conclusion	Presents the conclusion upon the problem statement
Chapter 10 Further Research	Suggestion for further research-based upon "loose threads" from this thesis

Table 1. Thesis structure, inspired by Wollan [2019]

Sammendrag

Det enorme fotavtrykket til bygg og anleggs-bransjen utfordrer stadig globale klimamål. Som konsekvens har bygg- og anleggsbransjen igangsatt flere sirkulærøkonomiske tiltak for å imøtekomme klimamålene, eksempelvis prosjektering for demontering (design for dissasembly). Flere av disse tiltakene gir miljøvennlige frukter med høstning etter at klimadatoene er utgått. Studenten uttrykte derfor en innledende hypotese at for å oppnå globale klimamål, må eksisterende legemliggjort energi utnyttes bedre etter sirkulæreøkonomiske prinsipper. Å sammensette prosedyrene som er nødvendige for å kartlegge den eksisterende bygningsmassen til materialbanker, vil kunne vise hvordan man kan effektivisere denne prosessen som vil kunne bidra til bedre ivaretagelse av legemliggjort energi.

Den innledende analysen fant tre trinn for å kartlegge eksisterende bygninger; trinn 1 - inspeksjonsprosessen, trinn 2 - kalkulasjonsprosessen og trinn 3 - modelleringsprosessen, med EUs initiativ *Buildings as Material Banks* mønsterpraksis for material pass som rammeverk. Ved å avgrensning oppgven rundt prefabrikkerte betongelementer, ble denne tre-trinns prosessen fremlagt for den norske og danske bygg- og anleggsbransjen gjennom en undersøkelse. Hensikten var å utrede realistisk tidsbruk og kompleksitet for disse tre trinnene knyttet opp mot en fiktiv to-etasjers case bygning på 300 m^2 og eldre enn 40 år.

	Median tid	**Kompleksitetsgrad (1-5)**
Trinn 1	17.5 timer	2.9
Trinn 2	45 timer	3.2
Trinn 3	37.5 timer	3.2

Analysen oppdaget trinn at 2 og 3 har størst behov for effektivisering. Videre ble det undersøkt og diskutert nærme hva i trinn 2 og 3 som skulle til for effektivisering; **repetisjon** for å sikre automatisering og **relevans** for å sikre riktig prioritering av ressurser. Diskusjonen fant ingen måte å internt forbedre tre-trinns prosessen, som reiste spørsmål om det derimot ikke var prosessen men bygningene som kunne sikre at relevans og repetisjon. Det ble derfor foreslått en kvantifiserbar fremgangsmetode for å identifisere bygninger som innehar disse to kvalifikasjonene. Identifiseringen ble gjort ved bruk av utvalgte parametere som tallfester relevans og repitisjon og gir bygninger en *Repetitive and Relevancy Score*, hvor en høy score indikerer effektiv kartlegging og lav score ineffektiv kartlegging.

Dessverre greide ikke studenten i løsningen å finne en vei utenom involvering av originalt prosjektmateriale. Dermed konkluderer oppgaven at bygninger kan kartlegges som materialbanker mer effektivt ved selektivt å velge bygninger som samsvarer med kriterier for repetisjon. Imidlertidig kan repetisjon kun identifiseres effektivt nok ved bruk av originalt prosjektmateriale. Uten dets eksistens, vil kartlegging av eksisterende bygg som materialbank fortsatt være svært kostbart.

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Acronyms

AEC Architecture, Engineering and Construction. 1, 2, 13, 17–19, 37, 43, 60, 61, 63

BAMB Building as Material Banks. 17, 20, 21, 29, 74
BIM Building Information Modelling. xv, 29–33, 42, 44, 45, 49–52, 55, 62, 64–66, 71

CDW Construction and Demolition Waste. 1, 3, 4, 18
CE Circular Economy. 2, 4, 15–17, 20, 33, 43, 45, 49–53, 60
CQ1 Case Question 1. xii, xv–xvii, 41, 44, 46, 48, 50, 53, 57, 59–64, 66, 71
CQ2 Case Question 2. xii, xiii, xv–xvii, 41, 43, 44, 46–48, 51, 52, 54, 57, 59, 61–63, 65, 66, 71
CQ3 Case Question 3. xii, xiii, xv–xvii, 42, 44, 45, 47, 48, 52, 55–57, 59, 62–64, 66

DFD Design for Disassembly. 2, 16, 19, 20

EPD Environmental Product Declarations. xvi, 23, 25, 45, 52, 60, 62

ISO International Organization for Standardization. 15

LCA Life-Cycle Assessment. xvi, 22, 23, 25, 26, 45, 50, 53, 55, 60, 62, 64, 65, 73
LCC Life Cycle Cost. xvii, 24, 26, 73, 74, 76, 77
LCI Life Cycle Information. 23, 30, 31, 59, 64, 66, 67

MFA Material Flow Analysis. 22, 23, 73
MIAT Material Inventory Analysis and Tool. 31, 32, 64
MP Material Passport. xv–xvii, 20–22, 24, 29–33, 45, 49, 50, 52, 54, 55, 59, 60, 62–66, 69, 71, 73, 74

R-Score Repetitive and Relevancy score. xvi, 68, 69, 72–74, 77
RCA Repetitive and Relevancy Component Analysis. 68, 69, 74, 75, 77, 81
RSL Reference Service Life. 26, 72

SE Structural Engineer. xv, 10, 27, 28, 43, 44, 46–48, 54, 60, 71, 76
SLCA Social Life Cycle Assessment. 24

VDC Virtual Design and Construction. 45, 49–52, 55, 62

1 Introduction

1.1 Background

In 2050, we live well, within the planet's ecological limits. Our prosperity and healthy environment stem from an innovative, circular economy where nothing is wasted and where natural resources are managed sustainably, and biodiversity is protected, valued and restored in ways that enhance our society's resilience. Our low-carbon growth has long been decoupled from resource use, setting the pace for a safe and sustainable global society.
[Council of European Union, 2013]

The Paris Agreement along with the United Nations´ goal of limiting global warming to 1.5°C above pre-industrial levels has forced industries and countries all over the world into change. Change into a more sustainable way of living, so that we leave opportunities not restrictions for those who shall inhabit this planet after us [UNFCCC, 2015]. Energy and resources are two keywords for challenges one strive to solve if the desired temperatures shall be retained. The footprint from today´s energy and resource-consumption for now leaves a negative mark on our planet [Network, 2019]. As a result, the world now needs to trend towards solutions and innovations who sees the words *waste* and *value* as synonyms, not antonyms.

The Architecture, Engineering and Construction (AEC) industry is noted as a major contributor to environmental degradation, and the industry produces unimaginable quantities of waste. According to Eurostat [2016] the AEC industry in 2016 stood for 36,4% of EU´s total waste generation, see figure 1.1. The Construction and Demolition Waste (CDW) consist of numerous materials, such as concrete, wood, plastic, metals gypsum, excavated soil and so on. Leading to this continuously flow of waste is activities such as demolition, construction, infrastructure, and maintenance. Unfortunately, according to Menegaki and Damigos [2018], it is estimated on a global basis that 35% of the CDW produced end up as landfills.

Alongside waste management, the AEC industry possesses one of the largest potentials for energy-efficiency improvement, hence its share on approx. 40% of global energy usage. [Sbci, 2009] According to Balouktsi and Lützkendorf [2016], energy efficiency is one of the key components of strategies to tackle climate change and to improve the security of energy supply as well as resource efficiency". However, the more energy-efficient the buildings become in their use phase, the more important the proportion of energy consumption associated with the other building life-cycle stages becomes, such as the production, construction, maintenance, deconstruction, and demolition.

1.2 Problem Field

1.2.1 Current CE Measures Impacts the Environment Post Sustainability Goals

Circular Economy (CE)´s principles are needed towards a sustainable AEC industry and the link between the AEC industry and CE is a red-hot research topic among scientists and researchers. The research addresses topics like design for deconstruction in new constructions, recycling, among others. Several solutions, innovations, and strategies, like Design for Disassembly (DFD) along with energy-efficient buildings are already implemented [Rasmussen et al., 2019]. While these are great initiatives and measures towards a lesser environmental footprint, most sustainability goals set by larger organizations and countries today and the one mentioned in section 1.1, has deadlines shorter than the average lifespan of modern constructions. The Energy Performance of Buildings Directive requires all new buildings in EU countries to be at a nearly zero-energy level by the end of 2020 [Recast, 2010]. Studies of low energy-houses have shown that the energy for production, which is included in the embodied energy, can account for 40–60% of the total energy usage [Nielsen, 1995]. The graph 1.2 shows how new energy-efficient buildings need several years before the environmental footprint is lesser than a conventional building, hence the cost of advanced materials and solutions. Normandin and Macdonald [2013] found that the average lifespan of a modern building varies from 60-100 years. In other words, new constructions with circular strategies implemented may not help enough

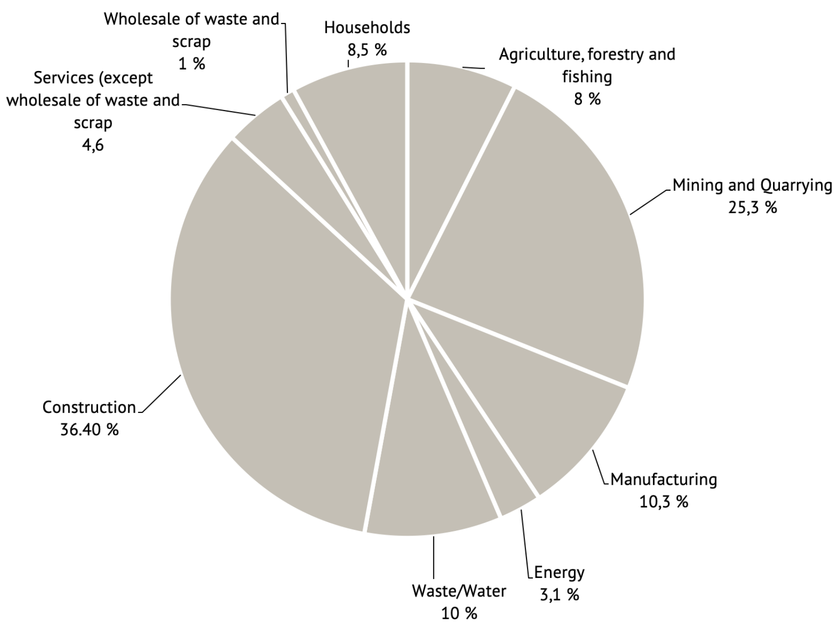

Figure 1.1. Waste generation by economic activities and households, EU-28, 2016 [Eurostat, 2016]

short-term if they origin directly from harvested raw resources.

Theme	**Past trends and outlook**		**Prospects of meeting policy objectives/targets**	
	Past trends (10-15 years)	Outlook to 2030	2020	2030
Circular use of materials	Improving trends dominate	Developments show a mixed picture		Partly on track
Material resource efficiency	Improving trends dominate	Developments show a mixed picture	Largely on track	
Waste generation	Trends show a mixed picture	Developments show a mixed picture	Partly on track	
Waste management	Improving trends dominate	Improving developments dominate	Partly on track	

Table 1.1. Status of ongoing sustainability goals [European Environment Agency, 2020]

1.2.2 Reuse of Construction Materials

When materials such as concrete, wood, plastic, etc. become landfills, they appear not only as pollution to a location, they become a downgrading of energy. From a building´s life cycle, one can trace different types of energy consumption. According to Dixit et al. [2013] the energy consumed in the life of a building other than the operation (space conditioning, water heating, lighting, operating building appliances, and other similar operational activities) is the so-called embodied energy of the building. Therefore, a building´s embodied energy can be categorized into various system boundaries and could range from the extraction of raw materials for manufacturing to demolition and landfill [Balouktsi and Lützkendorf, 2016].

Reducing CDW landfills implies better conservation of the embodied energy of the current building stock and higher reuse of construction materials. As table 1.1 shows that the goal

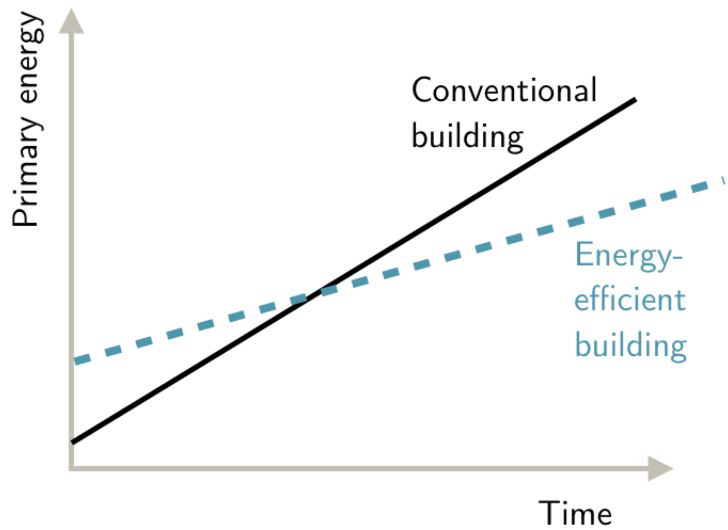

Figure 1.2. Conventional versus energy-efficient buildings [Balouktsi and Lützkendorf, 2016]

of material resource efficiency towards 2020 in the EU is largely on track. However, trends and outlooks towards 2030 show circular use of materials as a mixed picture along with resource efficiency and waste generation. Construction waste originates from either ongoing or future construction projects while demolition waste differs from that it already exists as the current building stock worldwide. Therefore, a key toward improving the outlook and trends, information on available reusable materials we have in our current building stock needs to be mapped and spread. According to Balouktsi and Lützkendorf [2016], the most important requirement for the assessment of the embodied energy of a building is that relevant data and information is available of the building materials and products that constitute the building. It is therefore essential that some of the CE-admiration focuses on preserving existing embodied energy and seek in-use construction materials as a usable resource, and not ending up as CDW.

1.3 Initial Hypothesis

To sum up section 1.2, current measures inspired by CE principles may not have the originally intended impact on ongoing sustainability goals, as the likely positive results from the measures are harvested post deadlines of short-term sustainability goals (2020,2030 and 2050). As a result, reusing construction materials is more of a futuristic scenario, where many of today´s buildings are designed for deconstruction with brand new materials.

To achieve global sustainability goals, existing embodied energy must be better utilized after the circular economy principles. Outlining the procedures and criteria needed for creating a material bank from the existing building stock, could show how to increase the overall disseminate of material information.

2 | Scientific Research Methodology

2.1 Project Method

2.1.1 Structure

The structure of this thesis is illustrated in figure 2.1. This thesis follows Aalborg University´s problem-based model, see figure 2.1. The figure illustrates an hourglass, symbolizing how the thematic focus starts wide and narrows in the middle towards a specific topic within the thematic focus before it widens out again. More specifically, the report approach from an initial hypothesis with the intention to guide the student and stay connected with the problem field through the research. After the hypothesis, an initial is conducted so a problem statement can be carried out.

2.1.2 Research Strategy

An inductive approach moves from single facts towards general principles and theories. The advantage of an inductive approach is that theories outlined from this strategy roots in reality or empiric content. Thus, they are always uncertain theories. A deductive approach draws logical conclusions from general towards less general principles. The advantage of a deductive approach is those conclusions outlined from this strategy become certain and true. Thus, their relevancy to reality is questionable [Tranøy, 2019].

The hourglass shape also represents this thesis approach to the deductive and inductive strategy, as the thesis starts with an overall deductive approach and opens for an inductive approach in the discussion.

2.1.3 Scientific Field of Philosophy of Science

This master thesis has an overarching standpoint in the pragmatic tradition, meaning that knowledge about reality is to be obtained from practical experience. Pragmatism gained a solid philosophical footing with John Dewey Thornhill et al. [2009] and considers what can be done and what can become, or simply that, which solves a problem of interest. This popularized maxim learning by doing is closely associated with the problem-based learning model adopted by Aalborg University is a pragmatic pedagogical model for learning [Universitet, 2015].

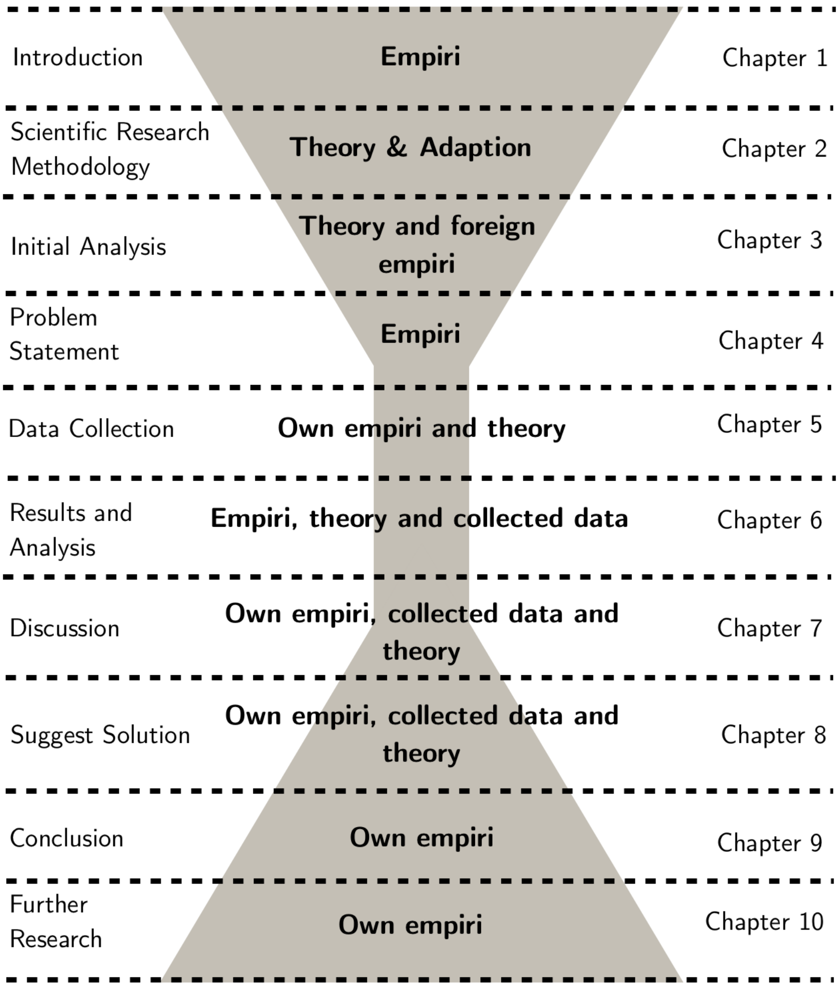

Figure 2.1. Thesis structure

According to Creswell and Creswell [2017] by following the pragmatic tradition the researcher may apply all available methods and emphasize understanding the problem in question, instead of focusing on certain methods for certain data collections. Figure 2.2 illustrates worldviews along with strategies, methods, and approaches.

2.2 Research Method - Mixed Method

From Creswell and Creswell [2017]: "Mixed methods research is an approach to inquiry that combines or associates both qualitative and quantitative forms." Thus, the mixed methods combines and involves philosophical assumptions with qualitative and quantitative approaches. Further, Creswell and Creswell [2017] emphasize that to ensure the full strength of a mixed method it is essential to apply both approaches in tandem. Only then may the research be greater than either qualitative or quantitative research. Creswell and Creswell [2017] also forwards mixed methods to be characteristic of:

- Typical philosophical assumptions
    - Pragmatic knowledge claims

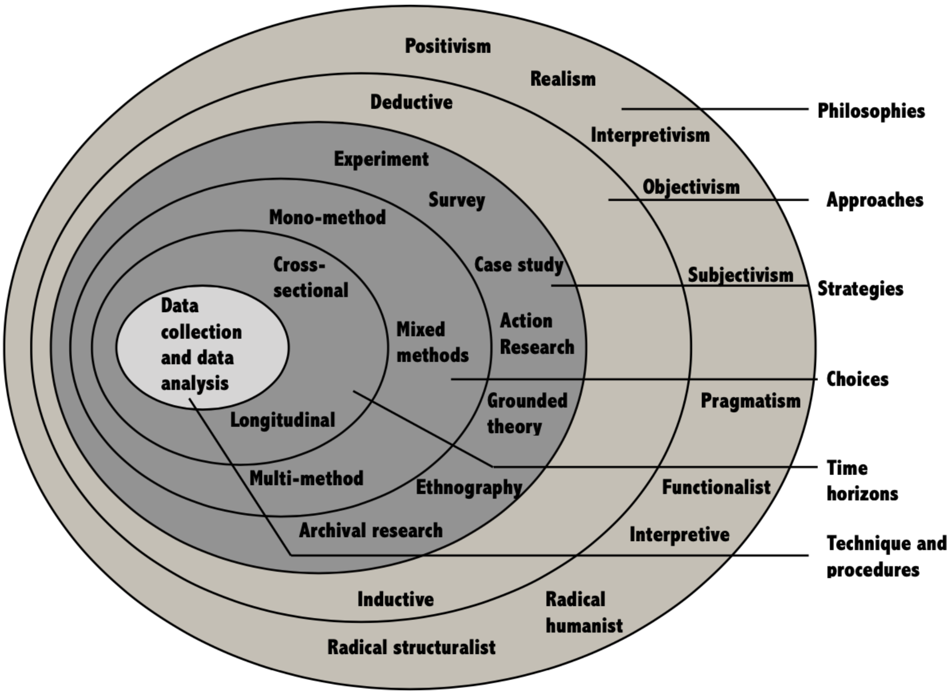

Figure 2.2. The Research Onion [Thornhill et al., 2009]

- Typically strategies of inquiry
  - Sequential, concurrent and transformative
- Typically employ these methods
  - Both open- and closed-ended questions.
  - Both emerging and predetermined approaches,
  - Both qualitative and quantitative analysis
- Typically research practices
  - Collects both quantitative and qualitative data
  - Develops a rationale for mixing
  - Integrates the data at different stages of inquiry
  - Presents visual pictures of the procedures in the study
  - Employs the practice of both qualitative and quantitative research

2.2.1 Strategy of Inquiry - Transformative Mixed Method

With transformative mixed methods, the researcher uses a theoretical lens as an overarching perspective over a research design that contains both qualitative and quantitative data. The lens as the purpose of setting a framework for topics of interest and methods for collecting data. If any changes or outcomes occur, the lens shall hold up as a guideline for how to react towards them. The lens itself could be a data collection method that involves a sequential or concurrent approach [Creswell and Creswell, 2017].

The transformative mixed method in this thesis will first conduct a literature review for secondary data before conducting a survey for primary data. The primary data in this thesis uses quantitative techniques and secondary data qualitative to compose the problem statement and survey. Phrasing differently, this thesis collects quantitative data from a qualitative survey. The student has further pragmatically adopted the initial hypothesis, which is outlined from a theoretical-based background and the following problem field in chapter 1, as the overarching lens for the thesis.

2.2.2 Survey as a Research Method

According to MacDonald and Headlam [2008] survey is a common method for collecting primary data where respondents respond to questions. The method is seen as a flexible way of collecting data, hence the researcher may end up with both qualitative and quantitative data. Surveys are often used when a researcher collects primary data from a larger pool of respondents. When proceeding with the survey as a source for primary data, it is important to understand who the respondents are, how to select them, what you want to ask, and how to organize the survey. Key considerations including strategies from MacDonald and Headlam [2008] before conducting a survey are:

- Can the population be counted?
  - A bias of the survey results can occur if the survey sample does not accurately represent the population.
- Are there language issues?
  - Respondents may have varying capacities for being able to complete written surveys or questionnaires.
- What are the geographic restrictions?
  - The geographic spread of the population to be surveyed will determine the method used for collecting your data, like the Internet, phone, interview, etc.
- Who is the respondent?
  - Type of persons, organizations, etc.
- What is the sampling frame?
  - A list of members of a population from which members of a sample are then selected.
- Are respons rates likely to be a problem?
  - Look at the profile of the people who did respond and satisfy yourself that they are about the same as the people who didn't respond – and also, that they're about the same as the overall population that you're sampling.
- Statistical significance.
  - Understanding your population, sample size, and response rates are important for calculating interval and confidence levels, which are vital in determining how many people you need to interview to get results that reflect the target population as precisely as needed.
- Ranking scales.
  - Commonly used when trying to ascertain the level of importance of a number of items. A list of choices is provided and respondents are asked to put them in order.
- Sliding scales.

– Used to discover respondents' strength of feeling towards an issue. Respondents are given a series of statements and asked how much they agree or disagree with the statement by using a sliding scale where numbers represent different strengths of feelings.

Besides the considerations above, MacDonald and Headlam [2008] highlight the importance of:

- Writing questions that are clear, precise, and relatively short.
- Not to use loaded or leading questions.
- Conducting a pilot survey.

2.2.3 Literature Review as a Research Method

Hart [2018] defines a literature review as "the use of ideas in the literature to justify the particular approach to the topic, the selection of methods, and demonstration that this research contributes something new". Literature reviews may, therefore, serve as a foundation for all types of research. Either functioning as a basis for knowledge development, provide evidence and, may, if well conducted, bring new ideas and directions for some scientific fields - a foundation for future research and theories. [Snyder, 2019].

2.3 Research Design

This thesis consists mainly of four elements, which figure 2.3 illustrates. The student intends to collect data from a mixed-method survey. As mentioned in section 2.1.1, the problem statement will be outlined from obtained information through an initial analysis in relation towards the problem field and initial hypothesis, see chapter 1. This hypothesis will function as the transformative mixed method´s lens, and is formed out of external literature research, where chapter 1 represents the findings and data from this research.

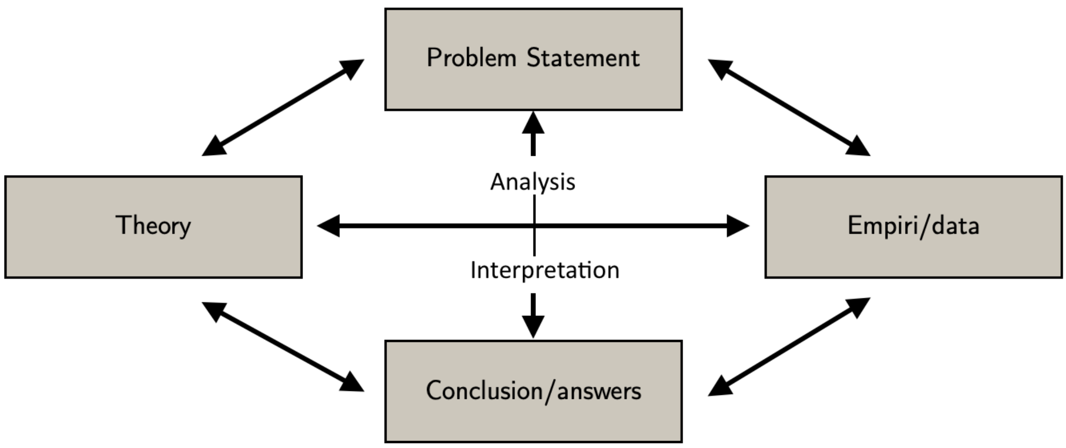

Figure 2.3. Scientific content, adopted from Andersen [2013]

2.3.1 Primary Data

According to Hox and Boeije [2005], "primary data are data that are collected for the specific research problem at hand, using procedures that fit the problem best."

Survey in this Thesis

An accordance with MacDonald and Headlam [2008] key considerations presented in 2.2.2, the student supposes that:

- The population cannot be counted but this is irrelevant since the medium of opinions (if the minimum number of respondents for the thesis is satisfied, see section 2.3.4) will be sufficient for this thesis.
- No language barrier exists, since the survey will be available in both English and two Scandinavian languages (Norwegian&Danish), and the geographic restriction for respondents is set to Scandinavia.
- The primary candidate for the survey is a Structural Engineer (SE), due to this report´s limitation, see section 2.3.6. Even so, contractors and other engineers are welcome to participate. As a result of this, a validation-section of the data is conducted in the analysis, see 6.2.1
- Sampling and aiming for respondents with certain relevancy to the topic.
- Responses rates may only be a problem if the overall rate is low, see section 2.3.4.

Respondent criteria are explained further in section 2.3.6 and 2.3.5. A pilot survey will be conducted through collaboration with colleagues. Further, the survey will have the following format and question-structure:

The **format** will be an internet-survey, using SurveyXact. An internet survey is chosen since the student except/seeks respondents from different companies and countries. SurveyXact is a survey-platform created by the Danish company Rambøll and SurveyXact is the preferable survey-platform at Aalborg University. Besides, taking in the thesis´s time-frame into account, an internet-survey makes the most sense. The student will communicate the survey towards relevant stakeholders by email.

Questions in the survey are based upon a "case", where information and data from a randomized "fictive" building are presented. The survey will use both Likert-scale sliders and fill-in boxes. A "blank" survey-scheme is attached in the appendix, see appendix A. Chapter 5 explains further how the survey was created.

2.3.2 Analysing the Results - Method

The analysis is divided into two sections; data validation and data analysis. The data is validated according the prescribed framework towards validity, reliability, and limitations, see section 2.3.5, 2.3.4 and 2.3.6. Unfitted data will be ruled out of certain analyses based upon the framework. Statistical correctness such as outliers will also be discussed, but not removed due to the smaller size of respondents and the type of respondents and questions.

Further, unbalanced data samples are evaluated, where highly unbalanced samples will not be compared after the principles described in the next paragraph.

In the data analysis, the different questions with belonging results are examined. The survey is sectioned into three topics, see section 5.2. The results from each topic are examined both alone and combined/in relation with results from the other topics, see figure 2.4. In questions where respondents are to estimate numbers (typing), the median value of the data is used for graphical analytical purposes. The median is preferred in most of the analyses instead of mean due to its ability to avoid a significant affection of outliers, and therefore gives a statistically more correct illustration of the data sample. Thus, when the amounts of respondents are the same for each of the questions, the median allows comparing question 1 and question 2, and not just data "inside one question".

2.3.3 Secondary Data

According to Hox and Boeije [2005], "On every occasion that primary data are collected, new data are added to the existing store of social knowledge. Increasingly, this material created by other researches is made available for reuse by the general research community; it is then called secondary data."

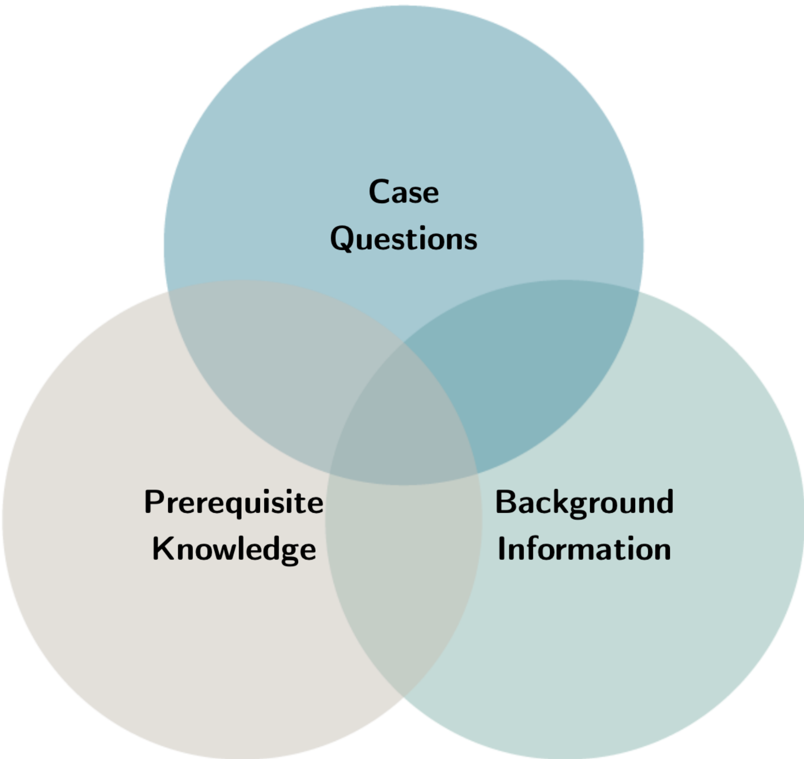

Figure 2.4. Analysing method for survey data,

Literature Analysis in this Thesis

Databases used for secondary data in this thesis are Scopus and Taylor & Francis Online and Sage among others, and the search engine Google Scholar. The literature review includes numerous research papers, conference proceedings, books, scientific reports, journal articles, manuals, handbooks, legislative documentation and regulations, and websites of official organizations. The student ensured to the best that the information found, used and presented is objective, from verified trustworthy sources and that the literature was published with the right scientific intent, see section 2.3.7

With the literature analysis launching and approaching from the initial hypothesis in section 1.3 sounding:

To achieve global sustainability goals, existing embodied energy must be better utilized after the circular economy principles. Outlining the procedures and criteria needed for creating a material bank from the existing building stock, could show how to increase the overall disseminate of material information.

the student chooses initial keywords such as circular economy, material passport, reuse and recycling, business models, buildings as material banks. From there, the student arched towards more specific keywords based upon results from the initial keywords, always with the initial hypothesis as the lens.

2.3.4 Reliability

Reliability is about being able to get the same results repeatedly, meaning to what extent results are consistent. In other words, other investigators should in principle be able to follow the same procedures and arrive at the same results [Bohnstedt, 2018].

In this thesis, the main concerns regarding the reliability are within the primary data - the survey. Therefore, this report´s reliability will depend on the number of respondents. Few respondents would imply low reliability for this thesis, while many respondents imply high reliability. Thus, the student will invite as many respondents as possible to conduct the survey, as long as they match the criteria set by this thesis limitations, presented in the section 2.3.6. It is hard to describe exactly what number of respondents is needed, but the student strives to have at least 10 respondents.

2.3.5 Validity

The student is interested in the results reflecting a truthful version of reality, and therefore emphasises stimulating the needs for a constant defendable validity. According to Bohnstedt [2018], validity confronts whether the selected measurement tool actually can measure the concepts it is intended to. Validity can, therefore, be said to be related to documentation and interpretation of data and to the extent the study measures what it should or how trustworthy the results are. Thorough interpretation of data can be based on background literature, which can create a framework for the interpretation of the collected data; an approach employed in this thesis. The practical implementation for maintaining the validity in this thesis will be done over two measures:

- Triangulation.
- A dedicated validation-section.

Triangulation helps to compare different types of data, where the purpose is to create a more complex understanding of a subject by combining different types of data. According to Creswell and Creswell [2017]:" If themes are established based on converging multiple sources of data or perspectives from respondents, then this process can be claimed as adding to the validity of the study". Standing in a pragmatic worldview, the student in this thesis adapts the triangulation thinking from *comparing data from different methods*, into a more *comparing questionable data from different sources* in the literature review. Triangulation is also used for the survey, ensuring the respondents´thematic relevancy by collecting three categories of background information. The analysis will also secure relevancy by emphasising respondents with the most experience.

The **dedicated validation-section** is about ensuring the validity of the data sample. Methods for doing so are explained earlier in this chapter, see section 2.3.2

2.3.6 Limitations

This thesis has an operating framework within the exercise of mapping existing buildings as material banks, specifically concrete precast elements, see section 2.3.6. Thus, the thesis will not cover the practice and concerns of extracting material. The thesis will neither account for the storage and sharing of information (material banks) and how to solve any issue regarding this. Warranty and responsibilities for *second-hand*-material will be slightly mentioned but the thesis´s intended purpose excludes it from the scope of this thesis.

Building Elements

This report focuses to thematise concrete structural building components and elements, especially during the initial analysis. This is due to the immense totality of the framework for reusing construction materials when approaching every single product and its material in a building. Structural elements in chosen since concrete is the most consumed man-made material and contributes with approx. 8% of annual global greenhouse gas emissions with over 4 billion tons of cement produced each year [Olivier et al., 2016].

Respondent Criteria

- Relevant occupation towards the thesis topic.
- Occupied in either Denmark or Norway
- Occupied within the AEC industry.

2.3.7 Source Criticism

Where data is collected from influences the outcome of the research and the thesis itself. Therefore, in this thesis, a critical approach towards literature read, influenced by and used, the objectiveness and subjectiveness of the source are examined toward its:

- Publisher and medium where the data published.
- Relevancy of the content.
- Authors´ motive and credibility.
- Citations and literature on which the content is based upon.

3 | Initial Analysis

3.1 Circular Economy

Traces of CE-thinking can be found in recent decades, but it is impossible to track the origin of CE towards a single date or author. CE´s general concept thereby its definition has been developed and refined by several thinkers and academics through time. Since the late 1970s there has been an uprising of CE´s popularity and the application of CE into the modern economic system, due to efforts of academics, thinkers and, businesses [MacArthur et al., 2013]. Even though missing the *inventor* of CE, several people strive to define it. According to Geissdoerfer et al. [2017] can CE be defined as "a regenerative system in which resource input, waste, emission, and energy leakage are minimized by slowing, closing, and narrowing material and energy loops. This can be achieved through long-lasting design, maintenance, repair, reuse, remanufacturing, refurbishing, and recycling." MacArthur et al. [2013] defines CE as a concept that involves the reuse of goods, product refurbishment, component re-manufacturing, cascading of components and materials, material recycling, biochemicals extraction, composting, anaerobic digestion, and energy recovery. International Organization for Standardization (ISO) holds and consequently works and update the international standard for CE: ISO/TC 323.

CE Strategy and Principles

The following bullet points followed by their belonging explanation are according the MacArthur et al. [2013], the main principles of CE strategy and thinking, also illustrated in figure 3.1 from the European Environment Agency [2020].

- Waste equals food.
- Design out waste.
- Build resilience through diversity.
- Use energy for renewable resources.
- Think in systems.

From a biological nutrient perspective, **waste equals food** symbolizes a restorative loop, and is a core value in CE. The value aims towards that one´s should always focus and emphasize to reintroduce products and materials back into the biosphere. Therefore, when a material/product/object is designed, keeping the biological and technical components in mind to fit within a cycle should be in focus. The importance of such design are among

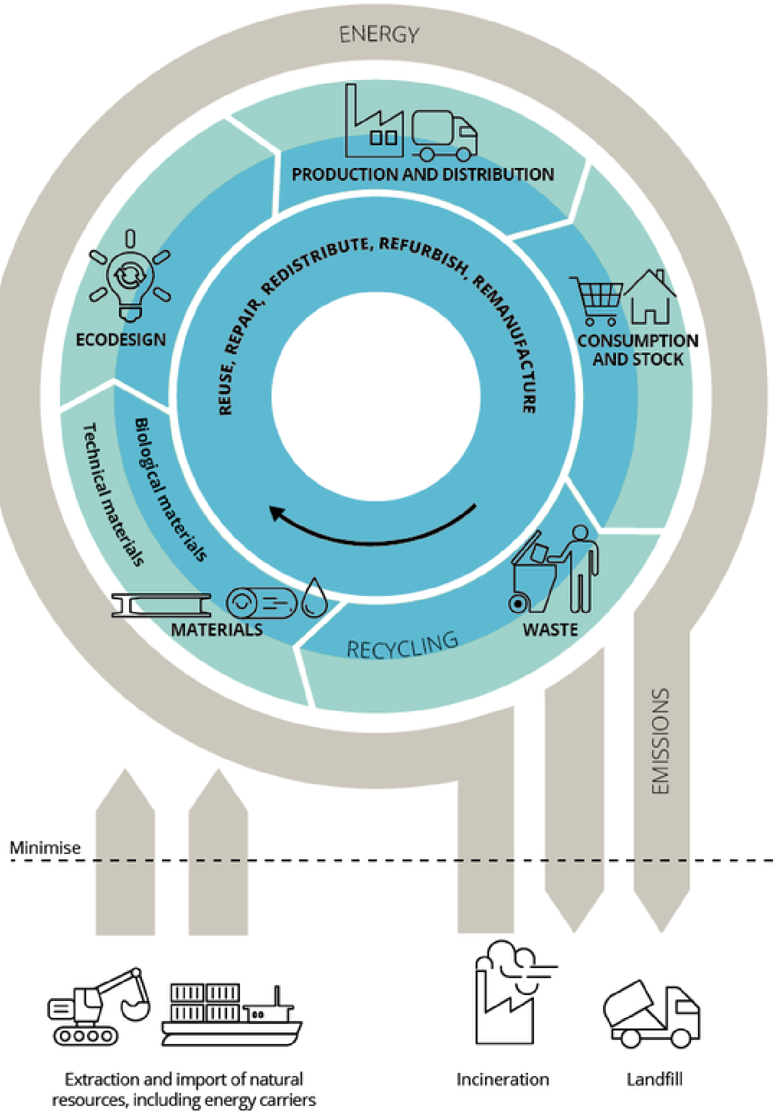

Figure 3.1. Circular Economy [European Environment Agency, 2020]

excluding toxic biological nutrients, with the end-goal to **design out waste**/DFD and refurbishment. Further, an economy, a nation, or a company can derive greater value from these principles by **building resilience through diversity** by sharing strengths and having a greater pool of resources to draw on. Such a system would be better able to bounce back from disruptive events than systems built for efficiency-maximization driven to the extreme results in fragility. In a world with increasing demands and consumption, for a CE system to work in the long term, there's a need to work towards **energy from renewable sources** →energy loop. Lastly, the ability to **think in systems** not singular is strategically important. CE is not one firm changing one product, CE is a system where several actors work several products in a effective circular flow of materials and information [MacArthur et al., 2013].

3.1.1 Circular Economy in the AEC Industry

Table 3.1 displays some of the most trending, important, and common plan of action for CE in the AEC industry according to Nussholz and Milios [2017]. The table divides strategies belonging after three life cycle phases; *material and component production*, *design*, and *end-of-life*. According to Adams et al. [2017], there exist significant literature in regards to CE incentives, but few wide-scale research and application in regard to the AEC industry.

Lifecycle phases	**Material and component production**	**Design**	**End-of-life**
Circular strategies	- Use fewer hazardous materials - Design for recycling - Prolonged lifespan - Design for product disassembly - Design for product standardization - Use of secondary materials - Take-back schemes	- Design for disassembly - Design for adaptability and flexibility - Design for standardization - Design out waste - Design for modularity - Specify recyclable materials - Design to reintegrate secondary production	- Disassembly - Selective demolition - Enable reuse of products and components - Closed-loop-recycling - Open-loop recycling

Table 3.1. Circular plan of action for increasing resource efficiency in the construction of buildings. [Nussholz and Milios, 2017]

3.1.2 Efficiency versus Effectiveness

Efficient - Performing or functioning in the best possible manner with the least resources

Efficient with eco-efficiency is related to a linear flow, ergo non-circular system. Eco-efficiency is therefore a technique to minimize bad environmental impact along a linear path. Eco-efficiency may be combined with recycled materials, but not materials designed and intended for reuse [MacArthur et al., 2013].

Effective - Adequate to accomplish a purpose; producing the intended or expected result.

Effectiveness with eco-effectiveness, seeks to create circular, healthy cradle-to-cradle systems. "Waste equals food" is the key principle for eco-effectiveness, the same as CE, see section 3.1. Eco-effectiveness seeks to maintain a material´s status (upcycling) [MacArthur et al., 2013].

3.1.3 Incentives and Challenges for Circular Economy in the AEC Industry

From Debacker et al. [2017], research conducted as a part of the research program/project Building as Material Banks (BAMB), investigated for the main barriers and incentives that lays ahead for a implementing CE in the AEC industry in EU. The BAMB-project is an EU-Horizon 2020 financed program for sustainable and future growth. Debacker et al. [2017] concludes that to achieve circularity, connections between and inside all the different phases of a system in the AEC industry is necessary so that support, communication, and information can reach the entire network of actors in the industry. The incentives and opportunities Debacker et al. [2017] found are:

Incentives and opportunities

1. Anticipating demographic changes and changing user requirements.
2. Eradicating CDW.
3. Lowering environmental and health pressures of the built environment.
4. Development of applied socio-technical solutions.
5. Development of guidelines and assessment instruments.
6. Exchanging valuable (resource) information within the value network.
7. Introduction of new commercial services on the market.
8. Introduction of innovative business models.
9. Increasing adaptability and versatile use of space.
10. Increasing life expectancy and the real value of real estate.
11. Decreasing renovation costs and added value of reusable building components.
12. Decreasing periodic maintenance and replacement costs.

Main barriers

1. Fragmented policy framework: from the EU to municipalities.
2. Conflicting Energy and Environment policy measures.
3. Lack of standardisation of qualitative data/information over the entire value chain of the product/building.
4. Intellectual property of material and product related data.
5. Linear construction industry models.
6. Higher complexity of disassembly compared to demolition.
7. General perception that reversible design solutions entail high financial cost.
8. Lack of certification and quality assurance for reclaimed products and recycled materials.
9. Lack of a business model framework related to a circular and reversible building.
10. Reversible building is largely unknown to the general public.

Business Model Innovation for Circular Strategies in the AEC Industry

"Companies that have aligned the core of their business or adjusted several business model elements tend to realize a larger number of circular strategies or achieve cycling of resources at higher value."

[Nussholz and Milios, 2017],

According to Nussholz and Milios [2017], demolishing-companies have few incentives for changing their practices in regards to disposing versus reuse. On the other hand, companies that want to reuse resources and materials (e.g. designers) is having a difficult time accessing the materials. When analysing the value chain for buildings from a construction perspective, the acquisitions of disposed materials and creating a marked for reused solutions are some of the major challenges for implementing the circular thinking in the AEC industry. This is, among others, due to "end-users" and customers of such products are concerned about the quality and functionality of the products.

Companies need to develop a range of new capabilities, "resources partners" (network), and methods to truly embrace and create value through circular strategies. Regardless of a company's type of business, concerns regarding quality and functionality forces companies´ business models to be more flexible [Nussholz and Milios, 2017]. Debacker et al. [2017] also points this out but emphasize an *intense collaboration within the entire value network*. In relation to resource partners, one should integrate the involvement of key stakeholders around important decisions like thematising design, components, conceptualization e.g. with the goal to coordinate dimensions of building components and standardize connection systems. As a part of the same operation, quality reassurance for reclaimed and recycled materials can be done.

Changing business models in the AEC industry has created value propositions beyond monetary; quality in relation to procurement. LEED and BREEM, which pursues reduced environmental impacts, and target customers that behold this as a high value are blossoming examples [Nussholz and Milios, 2017]. Debacker et al. [2017] highlights the importance of *business creation through product service systems*. Business models should draw up with the idea of a situation beneficial for both end-users and manufacturers. Business opportunities should be created through *user-ship* and not *ownership*, by creating performance-based product services, see figure 3.2.

3.1.4 Design for Disassembly and Deconstruction

Deconstruction can be seen as the gentler approach towards demolition, where the intent is to restore and reuse the materials. DFD is the practice and method used to ease deconstruction processes and procedures through planning and design. Both DFD and deconstruction are essential strategies to achieve circularity for the materials [Rios et al., 2015]. Figure 3.3 shows how DFD affects Kibert and Chini [2000]´s waste management hierarchy and how the end goal of DFD and deconstruction is to reduce landfill.

Rios et al. [2015] states the following principles for DFD to be:

- Proper documentation of materials and methods for deconstruction.
- Design accessible connections and jointing methods to ease dismantling.

Figure 3.2. Manufacturing versus service [Cohen, 2012]

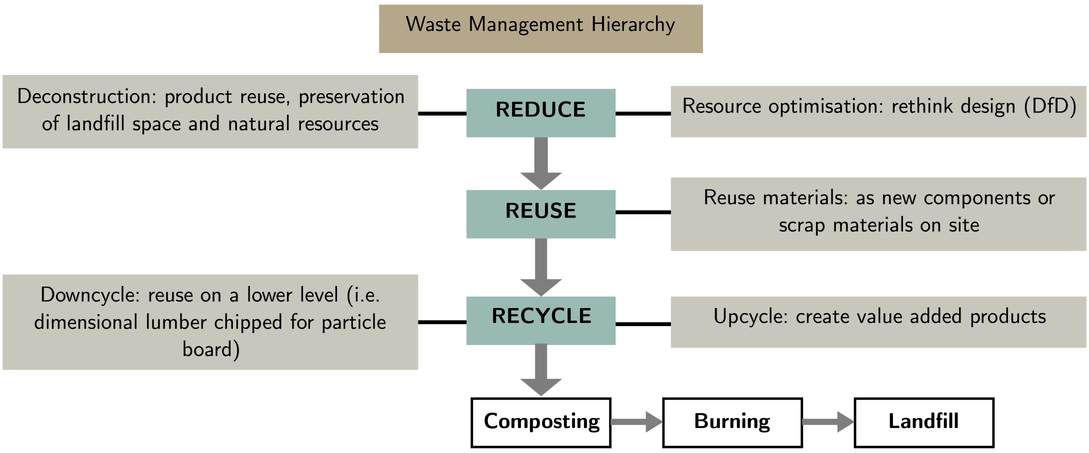

Figure 3.3. Waste Management Hierarchy adopted from Kibert and Chini [2000]

- Separate non-recyclable, non-reusable, and non-disposal items, such as mechanical, electrical, and plumbing.
- Design simple structures and forms that allow the standardization of components and dimensions.
- Design that reflects labour practices, productivity, and safety.

3.2 Material Passport

According to Luscuere [2017], MP is a tool/equipment available to use and support different stakeholders/actors in a construction project, manufacturers, municipality, clients e.g. Merrild et al. [2016] addresses MP as one of the key preconditions to put circular life-cycles for building and its materials into practice. MP intends to document and supply the stakeholders with accurate and adequate information on various inquires in relation to a product´s design. Information in a MP includes, but not limited to, composition, structure, manufacturer, contractor etc. By supplying such information, an MP operates as a mechanism for innovation both inside and outside CE strategies [Luscuere, 2017].

Previously mentioned BAMB defines MP after Hansen et al. [2012] as a *Nutrient Certificate*: “Nutrient Certificates are sets of data describing defined characteristics of materials in products that give them value for recovery and reuse. The certificates are a marketplace mechanism to encourage product designs, material recovery systems, and chain of possession partnerships that improves the quality, value, and security of supply for materials, so they can be reused in continuous loops or closed loops or beneficially returned to biological systems. This is done by adding a new value dimension to materials quality. This new dimension is based on the suitability of materials for recovery and reuse as resources in other products and processes.”

MPs may serve for a single material, product(s), and entire system(s). The information in the MP can either be generic for abstract product(s) or specific if some information only applies for a certain single product [Luscuere, 2017]. The MP can further define a material´s ability to recover, by assembling characteristics such as its correlation with DFD. Further, an MP can and should be generated by more than one party/actor, and thus, contain data from different sources with information intended for different purposes. Therefore, a MP need and must have the functionality to deliverer different information towards different stakeholders at different times.

3.3 Material Passport - Best Practice

As part of the BAMB-project, Heinrich and Lang [2019] developed the report "Material Passport - Best Practice", outlining a framework for MP. This best practice is explained below by presenting content and processes for a MP.

3.3.1 Material Data for a Circular Economy

For their best practice MP, Heinrich and Lang [2019] departures from four subcategories as figure 3.3.1

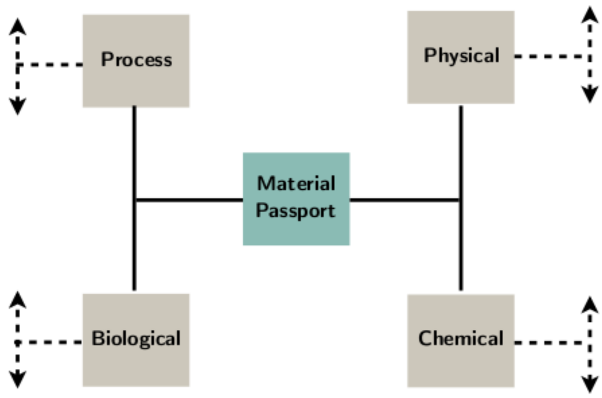

Figure 3.4. Overview over best practice MP, adopted from Heinrich and Lang [2019]

Biological properties like biodegradability e.g. are required when using renewable materials and products so a material can be considered for reuse or not. **Physics** addresses a building´s physical aspects such as energy & thermal performance, transparency, hygroscopicity, sound- insulation & -transfer, fire protection, ventilation & air-tightness, illumination properties with more. The **Chemical** ingredients in a material are important for mapping any environmental and human risk, and for evaluating the material´s reusability. The ingredients define a material as a product and its functions [Heinrich and Lang, 2019]. According to McDonough and Braungart [2012], who is behind the Cradle to Cradle Certification (now run by the non-profit independent institute *Cradle to Cradle Products Innovation Institute*, states that in a product, materials and substances at a concentration of 100 ppm (parts per million) or higher must be reported. In addition, any illegal substances must be reported under any circumstances. Table 3.2 displays the content of **processes** along with more information on the other three categories. The **Processes** among others involve investigating material health, information on transportation and logistics, use and operate phase, disassembly and reversibility.

Material Passports	
Physical	Dimensions **Structural Data** Building Physics Fire resistance Optical Lifespans & durability Recycling & re-use potentials
Process	Product labels & certification Registration Policy Standards & design codes BIM Actors Ownership Design for disassembly & reversible structures Installation, use & extraction instruction Function Unique identifiers Material flows
Biological	Renewable / non-renewable Untreated / treated Decomposability Recycling & re-use potentials
Chemical	Chemical composition Health & safety LCA - environmental assessment LCC - economic assessment Resistance & stability Lifespans & durability Recycling & re-use potentials

Table 3.2. Content and processes of an MP, adopted from Heinrich and Lang [2019]. Structural data continued in table 3.3

Structural Data
Compressive strength
Load bearing
Stability
Resistance

Table 3.3. Structural Data [Heinrich and Lang, 2019]

3.3.2 Life Cycle Management

Material Flow Analysis

A Material Flow Analysis (MFA) is a tool for estimating and measure flows and stocks of materials through space and time. An MFA is usable for a data and inventory analysis, as a part of an Life-Cycle Assessment (LCA), see section 3.3.2. The MFA has the purpose of providing information on resource usage, production steps, material losses, and waste creation, among others [Heinrich and Lang, 2019]. Figure 3.7 illustrates MFA as a system that balances inputs and outputs for operations and processes and sets these into relationships. In addition to track materials and measure material accumulation in individual processes, Heinrich and Lang [2019] describe the following usage for MFA:

- Balancing industrial input and output to natural ecosystem capacity.
- Dematerializing industrial output (i.e. reducing material use).
- Creating loop-closing industrial practices controlling pathways for material use and industrial processes.
- Resource management.
- Process chain analysis.
- Balancing flows between the anthroposphere and the environment.
- Modelling elemental composition of products and wastes.

Life Cycle Analysis

An LCA is method to analyse and estimate environmental consequences, effects, and aspects of a system through its life cycle. The system could be anything from a simple material or product, to an entire building. ISO14040 and ISO14044 provide a standardized LCA-framework for how to use and apply the analysis. Figure 3.6 illustrates the method and stages for an LCA.

Figure 3.7 shows the different stages for when conducting an LCA. The *goal and scope definition*-stage seek to define system boundaries, functional units, etc. The *inventory analysis*-stage tries to map all the relevant processes (like production steps, transportation, recycling, reuse, etc.) defined by the scope and the system boundaries (MFA may be used here). The *impact assessment*-stage aims to link developed inventory and data set towards potential environmental impacts that can be obtained from LCA-information (hereinafter LCI, e.g. Environmental Product Declarations (EPD) [Heinrich and Lang, 2019].

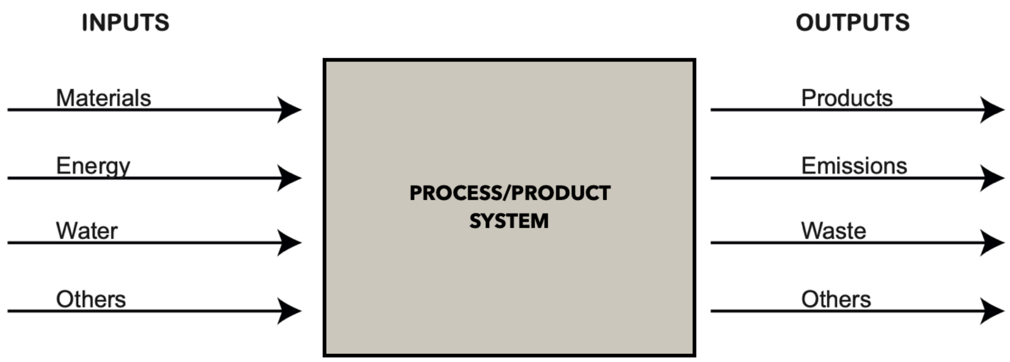

Figure 3.5. Material Flow Analysis [Heinrich and Lang, 2019]

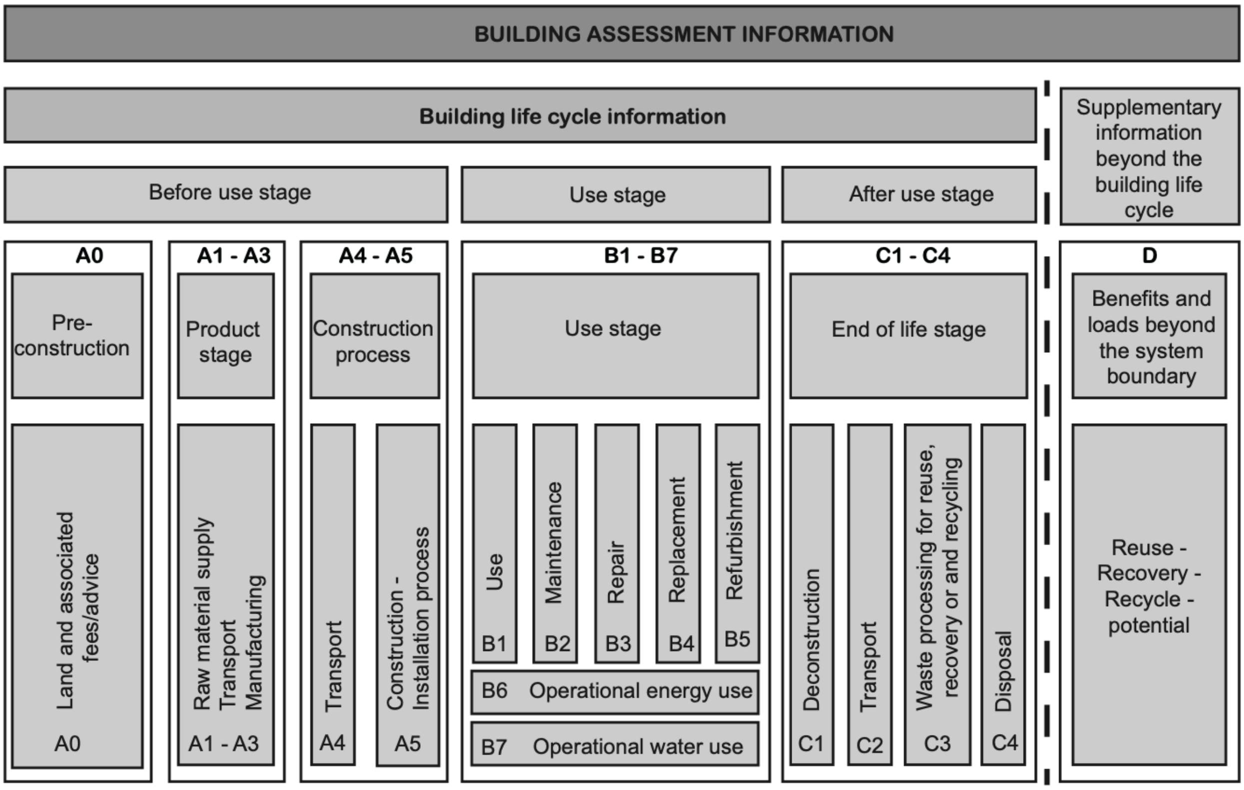

Figure 3.6. Classic life cycle phases of buildings and building products [European Innovation Partnership, 2012]

Social Life Cycle Assessment – Social Analysis

A Social Life Cycle Assessment (SLCA) aims to analyse social and sociological aspects of systems, materials, etc. The result of the analysis should enlighten both negative and positive effects of a product through its time [Life Cycle Initiative, 2017]. Table 3.4 shows SLCA-indicators for a SLCA. The SLCA are most commonly used for a specific product, hence general data won´t give any useful information. As for now, there are no standardized framework for SLCA, since the method is under development and a fairly new introduction to the life cycle management family [Heinrich and Lang, 2019].

Life Cycle Costing

Life Cycle Cost (LCC) is a method to determine the total cost of a system during its life cycle. The method is highly important due to the large influence economic factors have when selecting a material or product. For a MP to work, it is important to know the owner of a product at a given time, so that either inquiry of acquisition of the system/material, or if situations where who is responsible of the system/material occurs. Ownership also may change, and it is therefore highly important to update this information in the MP, which a process which LCC analysis may provide with [Heinrich and Lang, 2019]. Table 3.4 shows the data requirements for an LCC

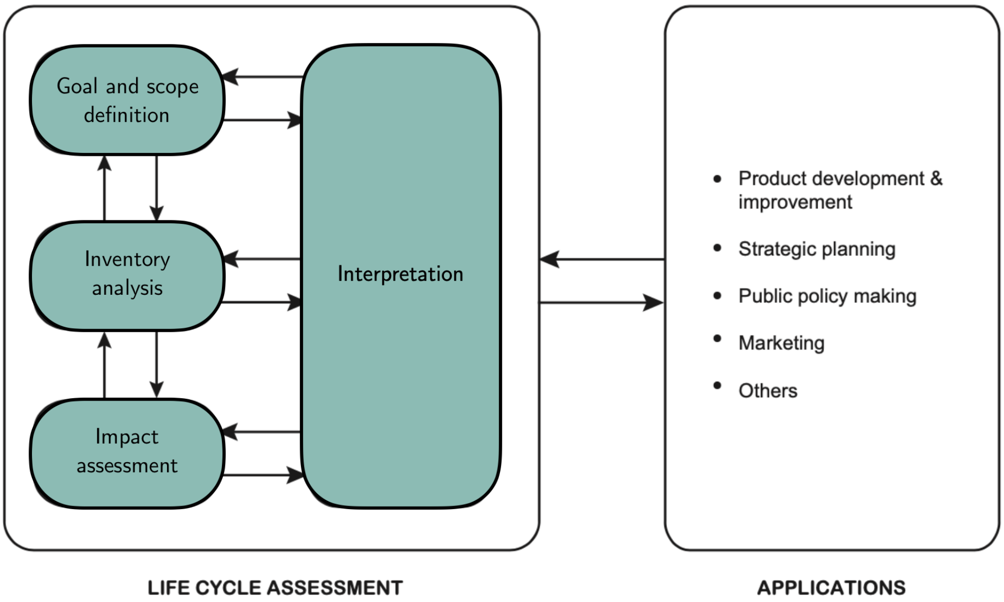

Figure 3.7. Stages of conducting a Life Cycle Assessment [International Organization for Standardization, 2006]

Social Life Cycle Assessment Indicators	**Data requirements for Life Cycle Costing**
- Child labour. - Fair salary. - Forced labour. - Health & safety. - Transparency. - Community engagement. - Cultural engagement. - Corruption. - Supplier relationships.	- Recommended retail price per unit. - Manufacturing cost. - Cost for maintenance and operations (e.g, cleaning, energy, water, upkeep). - Cost for service models. - Cost for re-use, landfill, etc. - Transportation and handling costs. - Potential income depending on re-use scenarios (e.g, urban mining, material banks. - Lifespans and durability. - Tax benefits. - Warranties. - Availability of spare parts.

Table 3.4. SLCA Indicators and LCC data requirements adopted from Heinrich and Lang [2019]

3.3.3 Assessment and Certification

It exists a diverse selection of alternatives when it comes to assessment and certification, and Heinrich and Lang [2019] categorize them by buildings, products, and others, see table 3.5. One example and mentioned in this table is the EPD. The EPD is a concise third-party verified and registered document with transparent and comparable information on the environmental performance of products throughout the life cycle. EPDs are therefore frequently used in an LCA. As with the LCA, EPDs are based on international standards: ISO 14025 [Del Borghi, 2013].

Assessments & Certification	
Building Certification & Assessment:	- DGNB - BNB - LEED - BREEAM - LEVEL(S) - OPEN HOUSE - Well Building Standard - Circular Building Assessment (CBA)
Product Certification & Assessment:	- Environmental Product Declaration (EPD) - Product Environmental Footprint (PEF - Material Circularity Indicator - Product labels
Others (e.g. Business, Process, Universal):	- Global Reporting Initiative (GRI) - Corporate Social Responsibility - Life Cycle Management - Risk Management- Quality Management - KPI Indicators (Carbon Footprint, Circular Footprint, Energy Demand, Ecological Footprint, Material Input per Unit of Service, Water footprint, Construction Waste, Chemical Footprint)

Table 3.5. Assessments & Certifications adopted from Heinrich and Lang [2019]

Reference Service Life

According to Heinrich and Lang [2019]; materials, products, and systems used in buildings have long lifespans compared to standard consumer goods. In construction, this is often referred to as Reference Service Life (RSL). Thus, among other functions, RSL can indicate when a product or system needs to be recommissioned. Further, data from a building or a product´s service life is essential for constructing analysis such as LCC and LCA.

3.4 Reclaiming Components and Materials

3.4.1 How to Reuse, Reclaim and Recycle Structural Components

Addis [2012] specifies methods for construction with reclaimed components and materials. Due to this thesis´s scope and agenda, reuse will thematise concrete structural components, see section 2.3.6 for limitations of this report.

Reusing In Situ

Reusing construction material and components in situ is the one method that may require the least effort, according to Addis [2012], with in situ meaning that the building with its components and materials to the best can be used or reused in the same location.

To reuse in situ and in general, it would be essential to investigate the components´ condition and suitability for the new project. In most cases, it would be necessary to repair and/or refurbish these components as well. According to Addis [2012] the cost of these operations would be lesser than demolition followed be reconstruction looking from a not-only monetary perspective.

When reusing any structural components, it is necessary to answer if the old structural frame will carry the new loads from the renewed purpose. Thus, a *structural appraisal* needs to be conducted by a SE. According to Addis [2012]; all structural/load-bearing components of buildings can be reused as long as they are insufficiently good condition to perform the duty required of them. Structural appraisal guidance for the SE varies from different countries and it usually exists standards for such a process. Most common in these standards are these listed procedures:

1. Search for, and desk study, of documentary evidence about the building.
2. Detailed investigation/survey of the building.
3. Assessment (including structural calculations and suitability for the new intended use.
4. Recommendations for work on the structure (repair, strengthening e.g.).
   [Addis, 2012]

Number 2, the detailed investigation/survey aims to plot exactly how the elements are structured, e.g. type of concrete. Procedures and operations in this investigation are among others:

- Conduct an examination of the condition of the whole building.
- Conduct a measured examination of the whole building.
- Establish the position and details of connections between the structural elements (This could mean the involvement of craftsmen due to the fact that structural elements may be covered in exterior materials, e.g. plaster).
- Conduct a structural inspection to establish the construction material, the structural system, and the form and cross-section of individual structural elements.
- Investigate for any structural defects e.g. corrosion.
- Investigate if any modifications are done on the original structure.
- Plot the dead loads carried by the structure
- Digging pits to expose the foundations
- Conducting geotechnical investigations to establish current ground conditions.
  [Addis, 2012]

Materials and Structural Assessment

According to Addis [2012]; the strength of reinforced concrete depends on the strength of both the concrete and the steel and the correlation of strength between the concrete and steel. Thus, *materials and structural assessments* are necessary. The chemical composition of the concrete together with a geological identification of the aggregate can determine its strength and density, with a core sample tested in laboratory [Addis, 2012].

Investigating the concrete for defects is therefore necessary. Next, document and identifying the location and size of the reinforcement steel is essential if the concrete

Some reasons for weaknesses in strength, quality, and durability for reinforced concrete.		
Design of material and structure	Quality of materials and construction	Deterioration in service
- Incorrect mix design (water-cement ratio) - Poor specification of aggregates - Poor reinforcement detailing - Inadequate design for creep - Poor external detailing (surface staining)	- Type of quality and cement - The Purity of water used - Low strength of aggregate - Weakness of reinforcement - Inadequate concrete cover to reinforcement	- Actions of carbon dioxide and acidic gases in the atmosphere - Actions of chemicals in groundwater - Weathering (wind and rain) -Inadequate maintenance and poor repairs - Settlement and movement of foundations

Table 3.6. Reasons for performance-reduction of concrete, adopted from Addis [2012]

should be considered for reuse. According to Addis [2012], identification processes towards reinforcement steel involves:

- Scrutinize original project material (if available).
- Identify the correct date of the building and research what design codes and laws that were in act at the time the building was constructed.
- A physical investigation by removing the concrete-cover in a non-crucial way to reveal the steel.
- X-ray and scanning technologies that can determine the location and size of the steel.

Warranty

When reusing concrete and materials, Addis [2012] states that the SE would be responsible for the appraisal, and any remedial work will be able to warranty the structural performance.

Reusing Salvaged or Reconditioned Products and Reclaimed Materials

Even if reuse in situ may be the most effortless solution for reuse, according to Addis [2012] it is more common to remove building elements during demolition or refurbishment and use the elements in another location and/or project. In general (but with exceptions) in situ-cast concrete cannot be reclaimed for use in another location. Precast concrete elements could be removed, refurbished, and reused, especially elements such as columns, beams, staircases, slabs, etc. The process would involve fitting the old elements for the new project, like cleaning, cutting, and replacing connections, among others. The likelihood of being successful with such a process is mostly dependent on two factors:

1. The condition of the concrete itself.
2. How components are connected - how easily can components be separated. Different methods of fixing components together have different degrees of reversibility.

3.5 BIMaterial - Process Design for a BIM-based Material Passport

As an underlying project of the BAMB, **BIMaterial** was a research project during 2016-2018. BIMaterial departed from the conclusion that *consumption of raw materials needs to be reduced in the building industry*, where the BIMaterial-group had the perception that in order to get there, *information about the material composition of buildings is required.* This was outlined from EU´s ambitions where the overall goal was to reduce waste, use fewer virgin materials, and increase recycling rates. Their (BIMmaterial) hypothesis underlined that for a decrease in virgin materials, information about materials composition in buildings must be known and publicized, to make possible re-usage and recycling of materials. Thus, a concept for a Building Information Modelling (BIM)-based MP was developed and tested [Honic, 2019].

3.5.1 Concept

Honic et al. [2019b]´s BIM-based MP aims to be an asset throughout the entire life cycle of a building, where the MP develops from an optimization tool in early stages (design/pre-construction) towards working as a material inventory in the last stages. Figure 3.8 illustrates the MP along the life cycle of a building and its relation to BIM, the MPGa, MGPb, MGPc, MGPd, see table 3.7.

This MP concept developed by Kovacic and Honic [2019] provides the following information from a building:

- Quantity of the materials embedded in a building, in tonnes.
- Percentage and tonnes of recyclable and waste materials in the building.
- Information (allocation) of where to find the materials in the building.

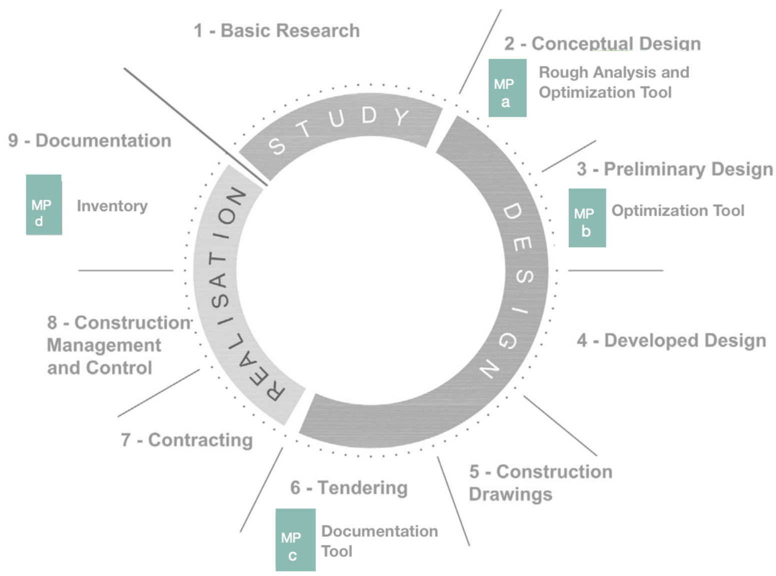

Figure 3.8. The MP along the life cycle of a building [Honic et al., 2019b]

- Separability of two enclosed materials.
- Ecological impact of the building - LCI.

The scheme which composes the information listed above consist of four levels: Building, Component, Element, and Material, see figure 3.9. The idea of the four levels is to isolate and discover what building elements have the highest potential for optimisation.

MGPa Conceptual design stage	MGPa works as a rough analysis and optimization tool with the aim of creating different versions and selecting the best Mono-layered elements
MGPb Preliminary design stage	MGPb works as an optimisation tool and adjusts thickness and layers for the different materials. Multi-layered elements
MGPc Tendering stage	MGPc works as a documentation tool and aims for acquisition of the tendering-related material composition.
MGPd Documentation	MGPd works as an inventory and documentation of the actual ("as-built") material composition of the building and as basis for a secondary raw materials cadaster.

Table 3.7. MP tools along a building´s life-cycle [Kovacic and Honic, 2019]

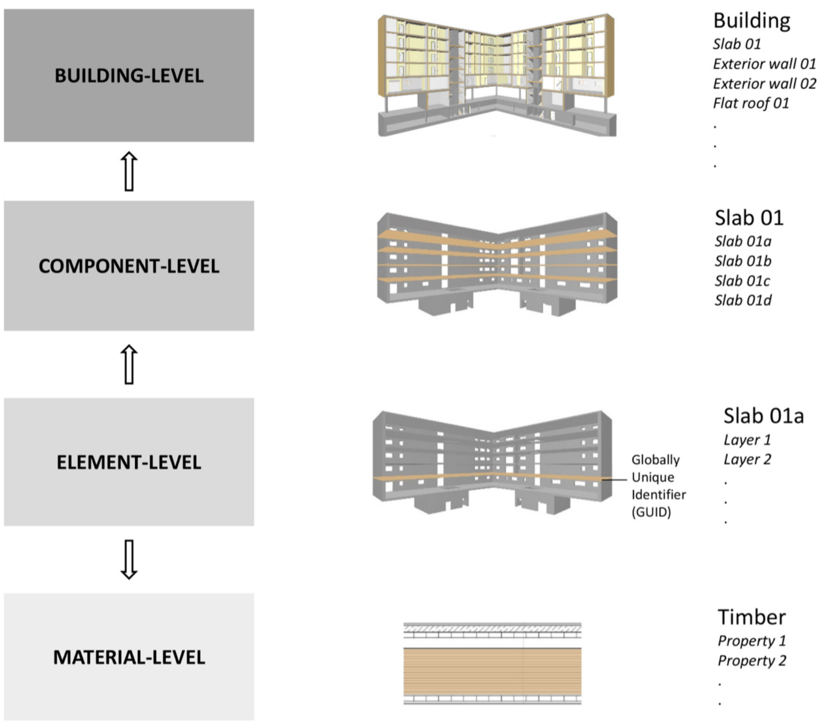

Figure 3.9. Scheme for a BIM-based MP [Kovacic and Honic, 2019]

3.5.2 Method

Figure 3.10 illustrates the method for a digitized BIM-based MP used by Kovacic and Honic [2019]. The first step of the method is modelling using e.g. ArchiCAD with help from a modelling guide and a control tool. The modelling guide defines the modelling requirements for an MP, e.g. classifications (walls, slabs, etc.), and sets requirements for the model in relation to what life-cycle stage it is, see table 3.7. The suggested control tool needs to control duplicates, collisions, etc., but also checks that predefined elements without properties are used. Kovacic and Honic [2019] suggest Solibri Model Checker for this operation.

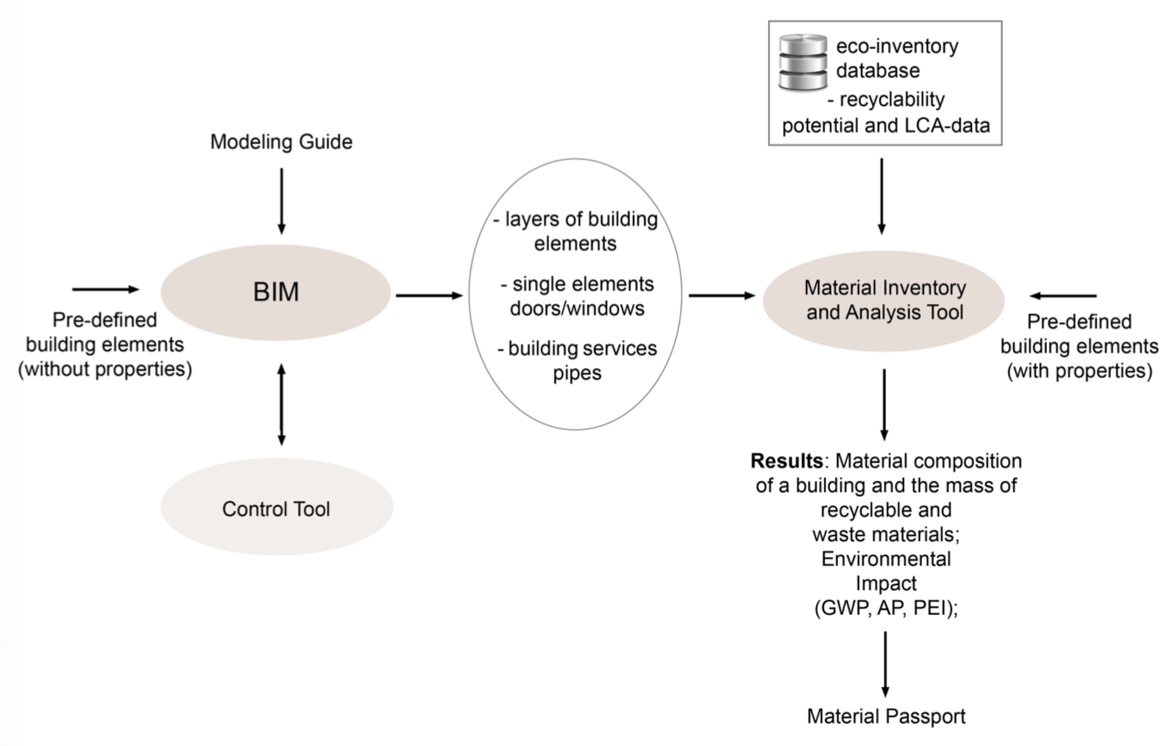

Figure 3.10. Method for a BIM-based MP [Kovacic and Honic, 2019]

The second step starts with sending the model-data (layers, volume, thickness, etc.) to a Material Inventory Analysis and Tool (MIAT) used for parameterization. Here, what Honic et al. [2019b] defines as MP-relevant data, are combined with the data from an eco-inventory and other LCI. The MIAT facilitates parametrization of each layer with e.g. recycling-relevant data, eco-data, and the data that are obtained from databases that certificate materials from a life-cycle perspective. For the final result, the MP is obtained through the MIAT and displays material structure, the share of recyclable materials and waste environmental impacts.

3.5.3 Challenges for the BIM-based MP

Several challenges occurred during the Kovacic and Honic [2019]´s research. First, inconsistent nomenclature in different eco-databases increased the number of manual operations, making the process of an BIM-based MP semi-automated. Further, Material compositions are not defined in early design stages, setting a restriction for designers to only use predefined elements. Also, it is hard to come around the need for extra manpower with prerequisite knowledge upon materials related to sustainability. Lastly, there is no consistent automated way of parametrization of materials in BIM, meaning a tool like MIAT is necessary. A MIAT requires some specific know-how knowledge to operate and even more manpower.

4 | Problem Statement

4.1 Updated Problem Field

After investigating upon reusing materials in the initial analysis, a remake of the problem field of 1.2 is necessary to compile a problem statement. The initial analysis found a CE-supportive "three-step path" towards existing buildings as material banks: Step one an investigation and scrutinising process fronted by Addis [2012]. Step two an investigation and calculation process where necessary structural data and information needed in an MP is gathered, fronted by Addis [2012] and Heinrich and Lang [2019]. Step three the modelling processes including BIM turning the materials into information for a BIM-based MP which can be used as material banks, fronted by Honic et al. [2019a]. Note that this thesis does not count for further processing of the information/data, like spreading, maintaining, etc.

The new problem field arises within the required resources to complete the three-steps mentioned in the paragraph above. The magnitude of the information needed for an MP alone proposes by Heinrich and Lang [2019] could be enormous. Further, the level of detailed necessary for a BIM-based MP proposed by Honic et al. [2019a] seems like a complex and time-consuming modelling job. From this problem field that questions to the magnitude of necessary resources required to create a material bank of existing buildings, the student outlines the following problem statement:

4.2 Problem Statement

How can the methods of mapping existing buildings as material banks be done more efficiently?

5 Data Collection

Where chapter 2 define the theoretical scientific method for a survey in both section 2.2.2 and 2.3.1, this chapter explains the more practical approach for the creation of the survey´s questions and structure. This framework is illustrated in figure 5.1 and explains the different steps and operations the student uses towards constructing the survey.

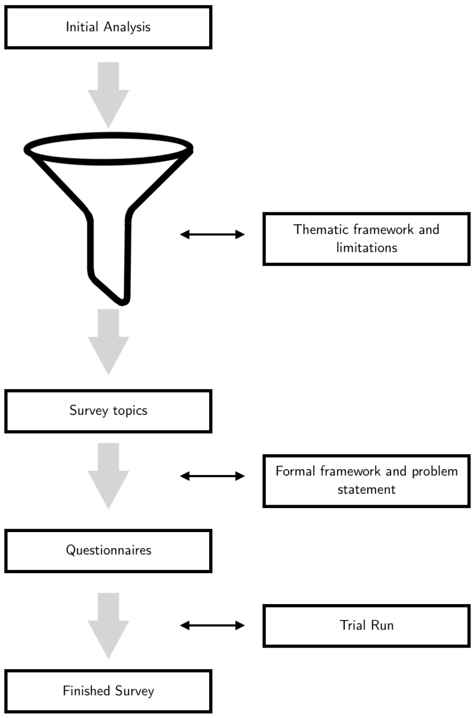

Figure 5.1. Framework for forming the survey

5.1 Filtering the Initial Analysis

Topics in the survey need to be relevant towards the initial analysis, hence the survey will root in existing literature and theory, minimizing bias from the student. Thus, the information and data from the initial analysis in chapter 3 is "filtered" with the thematic framework for the report and by doing so designing the survey´s main topics.

5.1.1 Thematic Framework

The thematic framework will be composed of both limitations set in section 2.3.6 and the initial hypothesis in section 1.3. The limitations set in section 2.3.6 has to a certain degree already filtered the initial analysis, where section 3.4, *reclaiming components and materials* isolated and emphasised concrete hence, **building elements**, see section 2.3.6 Further, an **existing building**-filter is put to practice, meaning that everything from the initial analysis surviving into the survey must be relevant to existing- and already constructed buildings, not future construction projects.

5.2 Topics

5.2.1 Background Information

To ensure that the respondent criteria are met, the first topic and section of the report will ask for basic background information from the respondent like occupation, experience, and job title.

5.2.2 Prerequisite Knowledge

The second topic will investigate respondents´ prerequisite knowledge upon this reports thematisation. The intention by doing so is to get an understanding of how known the concept of material passport, reuse, etc. among designers. Prerequisite knowledge should also help to validate and analyse the answers when compared to the last topic of the questionnaire, the case-questions.

5.2.3 Case

The last topic of the survey will concern around a case. As mentioned in section 2.3.1, the student has constructed a fictive building, see figure 5.2 where the steel- and concrete-skeleton is illustrated. The respondent is given the illustration, along with the following description:

- Constructed between 1960-80s.
- Steel and concrete structure.
- Precast concrete elements.
- 2 floors.
- 300 m^2 in total (150 m^2 per floor).

The purpose of this information is not to precisely reflect an actual building from the 1960-80s, nor have a correct structural composition. It is rather to give the respondent a somewhat simple and small building-complex so that he/she can make estimates in regard to the questions asked. The case questions will be based upon the *filtered* initial analysis combined with the problem field, the three-step path towards mapping existing buildings as material banks:

- The investigation process - Addis [2012]
- The calculation process - Addis [2012] & Heinrich and Lang [2019] & Honic [2019]
- The modelling process - Honic [2019]

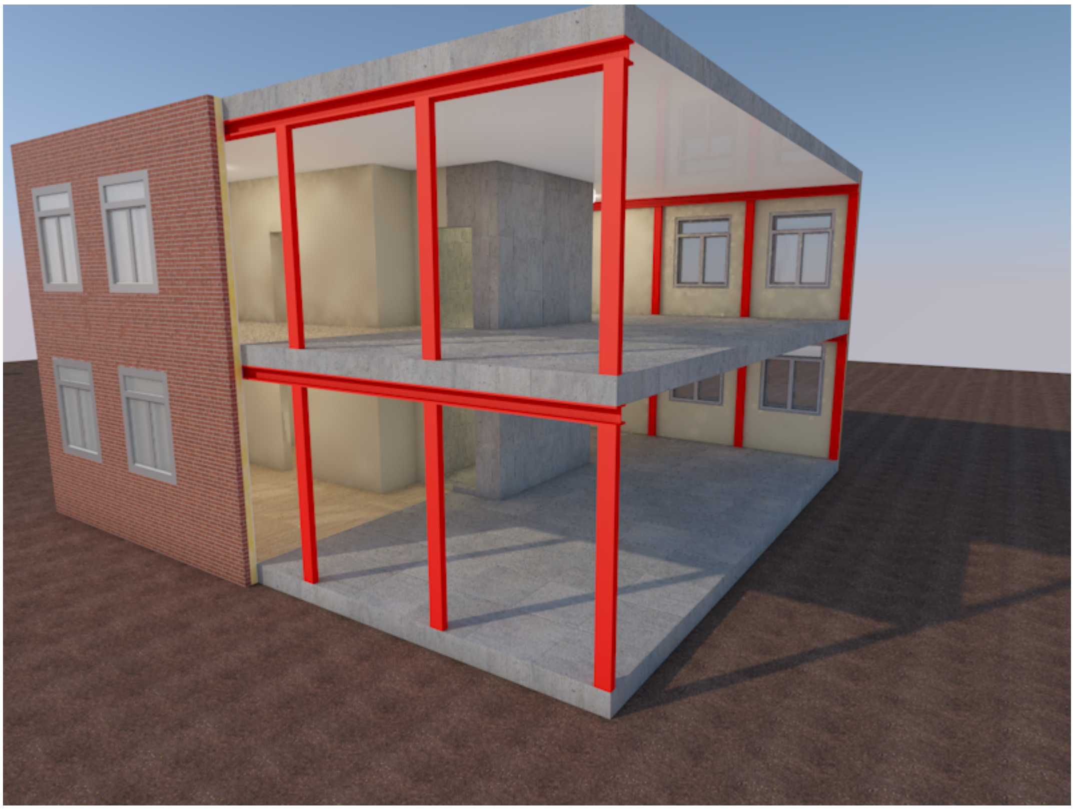

Figure 5.2. The case building illustration used in survey. Modelled and rendered with ArchiCAD 23

5.3 Trial Run

A trial run was completed with the student´s former student-colleagues from Norway who currently are occupied in the AEC industry. Feedback was collected upon the survey and as a result, some minor changes improving the survey´s interpretability and clearness were done. Next, the survey was forwarded to the student´s supervisors, resulting in a last change where the respondents´ opportunity to describe their pre-conditions for answering the way they did, was removed.

5.4 Survey

The complete survey is attached in the appendix, see appendix A.

6 Results and Analysis

6.1 Results

This section displays a graphical representation of the data, untouched from analysis intentions. The results here are displayed as the questions were asked. For raw non-graphical data, see appendix B.

6.1.1 Background Information

This section displays data related to the respondent´s background information. Note that in table 6.1, which shows the respondents claimed job title, the number of respondents stating the same title is numbered in parentheses. Every unique job title sampled in the survey is presented, even if it is a question of translation. The number of respondents declined along with the questionnaires, and why so will not be discussed. Thus, the number of respondents for each question is displayed with each result for reader´s clearness.

	Job Title	
Hydrauliker (1)	Prosjektingeinør (4)	Rådgiver Energi og Miljø (1)
Formann Tømmer (1)	Prosjektleder (1)	Bygningskonstruktør (5)
Vegingeniør (1)	Konstruktør (1)	Prosjektingeniør Kalkulasjon og innkjøp (2)
Konstruktionsingeniør (19)	Design Manager (1)	BMS Specialist (1)
El-ingeniør (1)	VVS ingeniør (1)	Project Manager (1)
Driftsrådgiver (1)	Structural Engineer (1)	Ingeniør (1)
Elektriske installationer (1)	Miljøingeniør (1)	Konstruktionsingeniør elementfabrikk (1)
Afdelingschef (1)	Områdedirektør (1)	Afløbsteknik (1)

Table 6.1. Job title

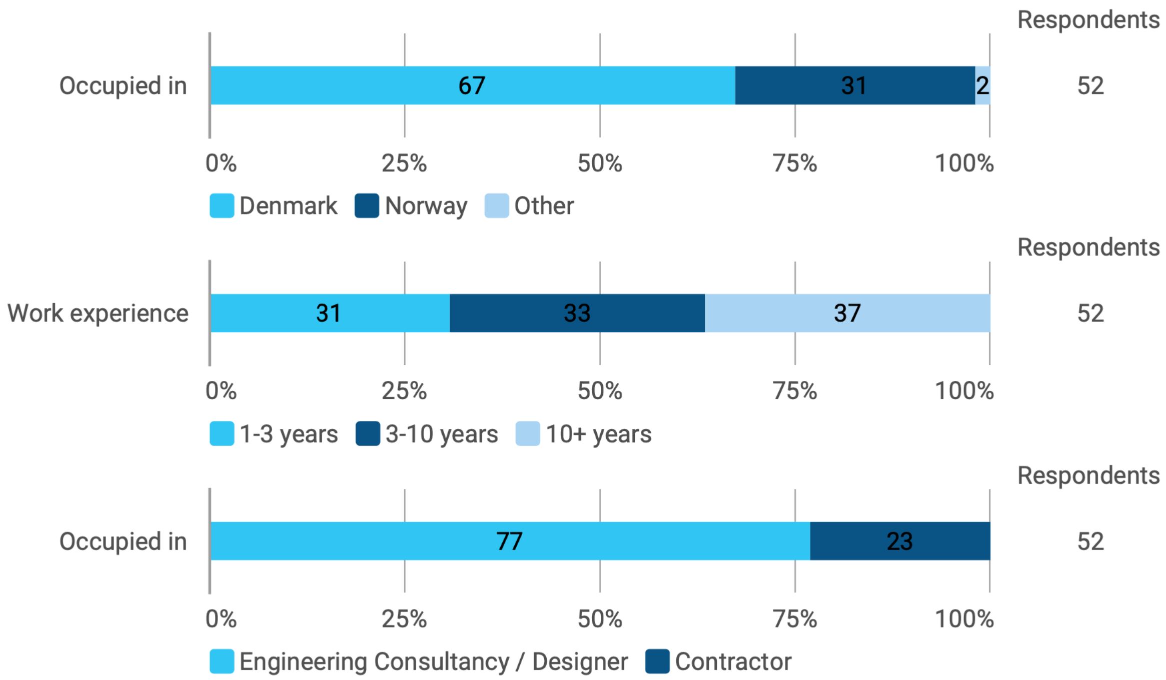

Figure 6.1. Background Information

6.1.2 Prerequisite Knowledge

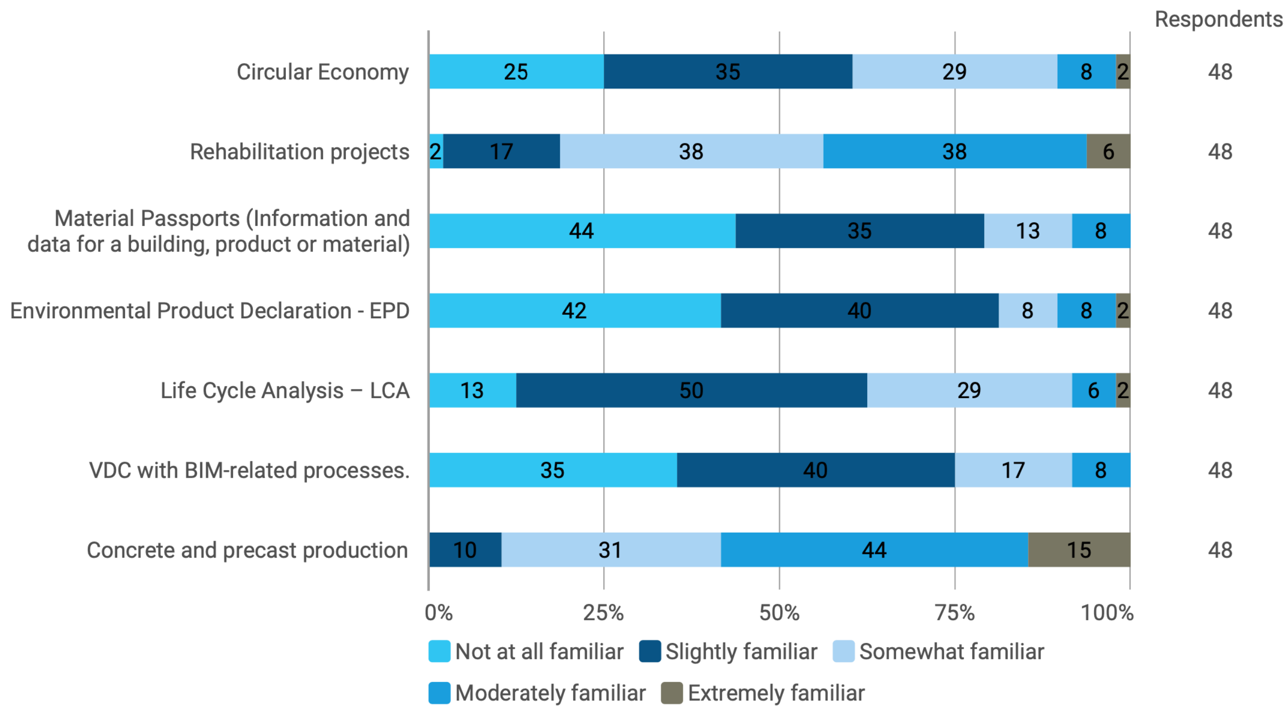

Figure 6.2. Prerequisite Knowledge

6.1.3 Case Questions

Case Question 1 (CQ1)

1. The first operation is to investigate and document the condition / "health" of all the prefabricated concrete elements in the case building. This would among other include inspection for damage, corrosion, scratches etc. as well as describe connections between the load-bearing systems in the case-building (e.g. between steel and concrete).

Case Question 1										
7.5	3	28	15	30	75	15	15	5	100	50
20	25	70	160	20	8	10	30	5	20	37
14	37	40	8	25	10	1	20	8	15	5

Table 6.2. Data from CQ1

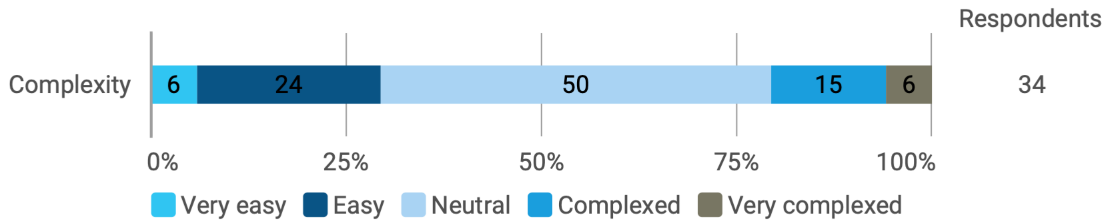

Figure 6.3. Complexity CQ1

Case Question 2 (CQ2)

2. The second operation is to calculate and determine design numbers (load capacity, type of concrete etc.) for the concrete elements and investigate and document reinforcement diameter, cover depth, volume, density etc. for the case building. The investigation should result into enough information you would find necessary for reusing the elements.

Case Question 2										
15	16	22	40	15	37.5	25	60	40	250	100
90	90	160	20	45	30	200	21	40	74	200
70	5	37	40	2	75	4	15	100	75	16

Table 6.3. Data from CQ2

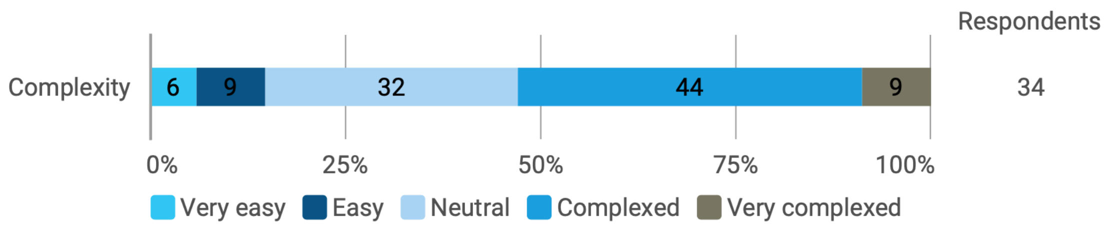

Figure 6.4. Complexity CQ2

Case Question 3 (CQ3)

3. The third operation is to design a structural BIM-model of the case-building down to a detailed material level, including properties of the concrete element like compressive strength, aggregate, reinforcement, dimensions etc. are described for each of the concrete element object in the model.

Case Question 3										
23	40	22	60	15	37.5	37	50	40	450	20
45	50	100	20	15	10	150	24	40	111	200
100	20	37	40	2	120	8	5	50	20	8

Table 6.4. Data from CQ3

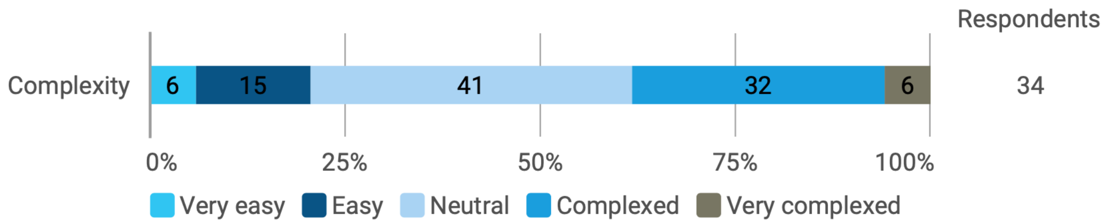

Figure 6.5. Complexity CQ3

6.2 Analysis

6.2.1 Data Validation

Outliers

With the case questions being estimates and numerical answers, outliers for the data sample needs to be tested to ensure the reliability and validity of the data even. Table 6.5 shows the outliers for the three different case questions. Looking into the different answers in table 6.2, 6.3 and 6.4 combined with the intended extent of the questions, the student chooses, as *originally planned*, not to exclude outliers. Excluding numbers above 63, 158, and 95 for the three questions, and including answers like 1 and 2 would decrease the validity of the sample. Instead, the student chooses to comment outliers if they are significantly identifiable.

	Lower range	**Top range**
Case Question 1	-25	63
CQ2	-62,5	158
CQ2	-25	95

Table 6.5. Outliers

Respondent´s Criteria

The original ideal respondent was SEs. As stated in section 2.3.1, "*The primary candidate for the survey is a SE*, but several other employees in the AEC industry were invited to participate in the survey for a more dynamic understanding of the AEC industry´s prerequisite knowledge regarding CE. It is therefore necessary to evaluate if some of the data from non-SE needs to be excluded. SE would include does who described their job title as either, *Konstruktionsingeniør* and *Structural Engineer*, see table 6.1.

	Median	Mean	Respondents
Case Question1			
Structural engineer	20	25.5	13
All respondents except structural engineers	17.5	30.3	20
Deviation	2.5	-4.5	
Deviation in %	14%	15%	
CQ2			
Structural engineer	45	78.6	12
All respondents except structural engineers	27.5	50.4	20
Deviation	17.5	28.2	
Deviation in %	64%	56%	
Case Question 3			
Structural engineer	40	74	13
All respondents except structural engineers	30.5	50.4	20
Deviation	9.5	23.6	
Deviation in %	31%	47%	

Table 6.6. Validating mean and median for case question 1,2 and 3

Table 6.6 shows mean and median for the case question, divided between respondents´ background (job title). CQ1 shows a 14% and 15% deviation between the SEs and all respondents except the SEs. Thus, all respondents are included for further analysis regarding CQ1, based upon the small deviation. CQ2 shows a 64% and 56% deviation between SE and all respondents except SE. Thus, non-SE are excluded for further analysis related to CQ2. CQ3 shows a 31% and 47% deviation between SE and all respondents except SE. The student finds a 31% median deviation along with step three thematising BIM arguments enough to include all respondents for further analysis related to CQ3. Note that the number of responding SEs that completed the survey is 13, meaning above the required minimum for reliability, see section 2.3.4.

Unbalanced Respondent Samples

Due to an unbalanced number of respondents in both occupational country and type of business, no analyses with these categories as a filter will be done.

- Norway 31%, Denmark 67%, and other 2%.
- Contractor 23% and engineering consultancy 77%.

Relevancy for Further Analysis

Not all of the subjects within the prerequisite knowledge displayed in figure 6.2 are relevant for direct analysis of the case questions. Only those subjects marked with Yes in table 6.7 is emphasized for a comment in the analysis. However, even if it is not commented, will all subjects be displayed in the graphs.

	Relevant?		
Subject	Case Q1	Case Q2	Case Q3
Circular Economy	No	No	No
Rehabilitation Projects	Yes	Yes	No
Material Passport	No	Yes	Yes
EPD	No	No	No
LCA	Yes	Yes	Yes
VDC with BIM related processes	No	No	Yes
Concrete with precast production	Yes	Yes	Yes

Table 6.7. Prerequisite knowledge and relevancy towards the case questions

6.2.2 Data Analysis

Prerequisite Knowledge

Investigating the results from prerequisite knowledge in figure 6.2 gives several outputs. *CE* is more unknown than a known topic among the respondents. Seemingly, most of the respondents state good familiarity with *rehabilitation projects*. *MP*s have the biggest percentage of respondents stating *not at all familiar*. Both *EPD*s, *LCA*, and *MP* are strongly connected, and the low knowledge about *MP* and *EPD* could imply that the type of work connected to *LCA* rarely involves product certificates. *Rehabilitation projects* with *concrete and precast production* are overall more known with the respondents, which makes sense due to the student´s target group for the survey.

The most dominating answer by the respondents for all topics except *concrete and precast production* is *Slightly familiar*. *Virtual Design and Construction (VDC) with BIM* is surprisingly unknown as a topic, which could imply that the terminology VDC is limited to the academic world, and the more trivial name "BIM" is more widespread, and a confusion when mixing the two of them may have occurred. It is, therefore, necessary to emphasize the outputs from CQ3 when deciding upon the respondent´s knowledge regarding VDC and BIM, see section 6.2.2

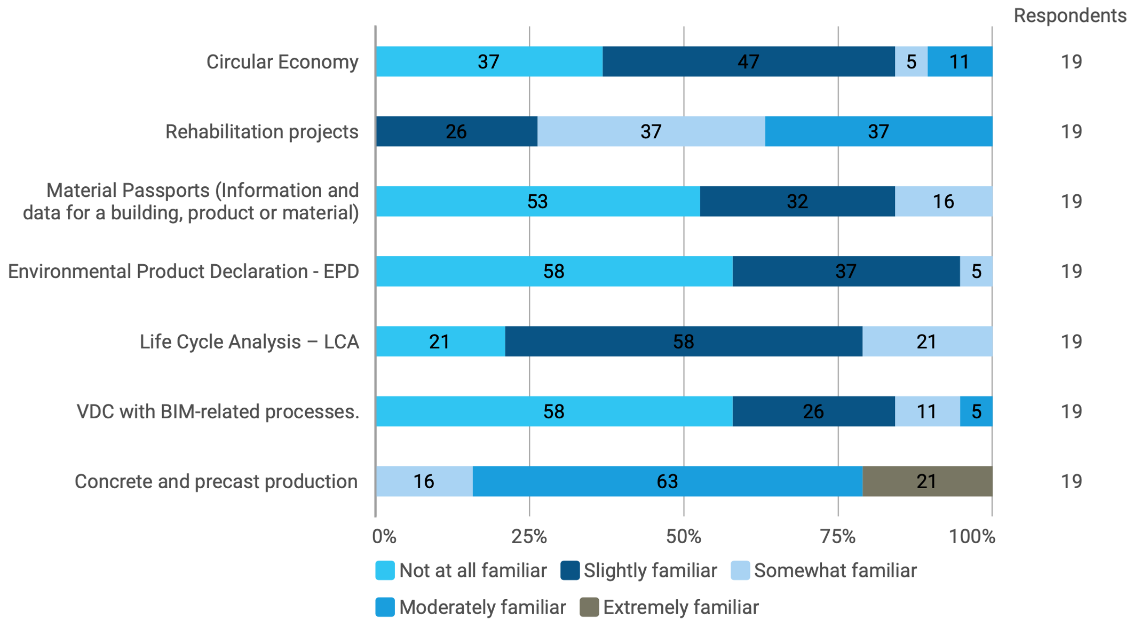

Figure 6.6. Prerequisite knowledge data from SEs only

Case Questions

	Median	**Mean**
Case Question 1	17.5	27.5
CQ2 (SE only)	45	7.5
Case Question 3	37.5	59.5

Table 6.8. Median and mean values from the case questions

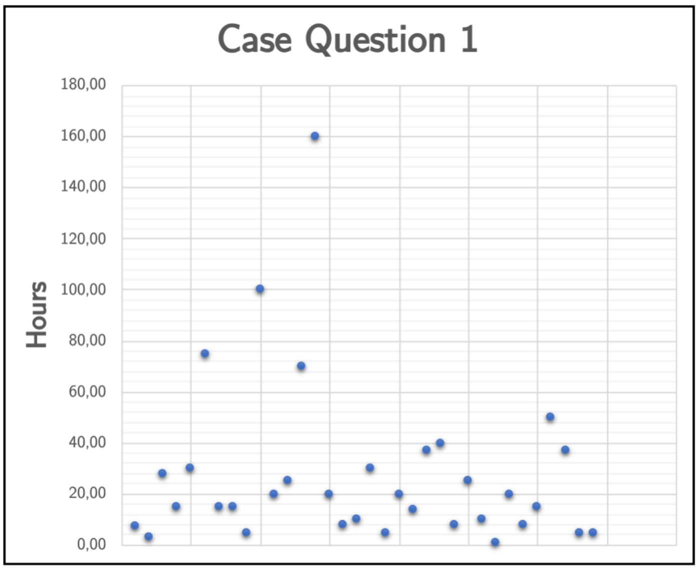

Figure 6.7. Data sample from CQ1

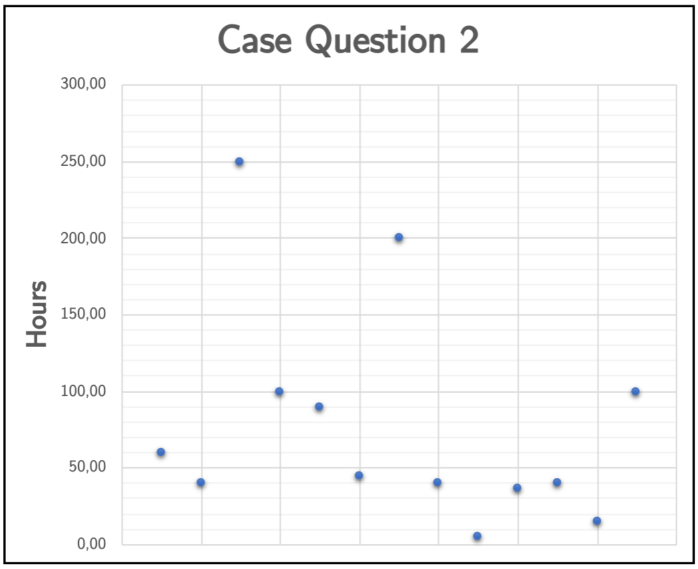

Figure 6.8. Data sample from CQ2

As stated in section 6.2.1, only data from the SEs are used for CQ2. The operation in this question involved both an investigation process and a calculation process, gave a median on 45 hours and an average on 78.5 hours. The level of complexity for CQ2 shown in figure 6.4, landed on a total complexity-score of 3.2.

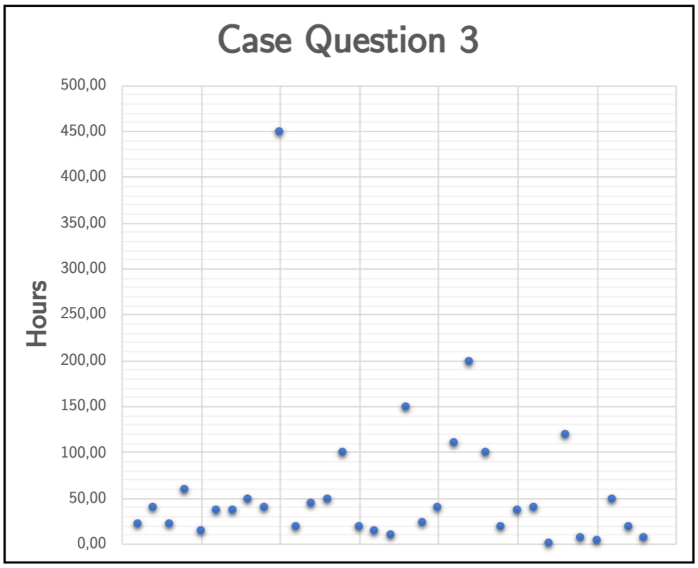

Figure 6.9. Data sample from CQ3

CQ3 in relation to manpower/hours is similar to CQ2, with this case question being more of a "desk job" with modelling the precast elements. This implies that modelling the precast elements is quite a job, as it would require the same resources putting together necessary design numbers and information. Looking at the overall complexity for CQ3 from figure 6.3, the overall score is 3.2.

Complexity and Hours-Estimations

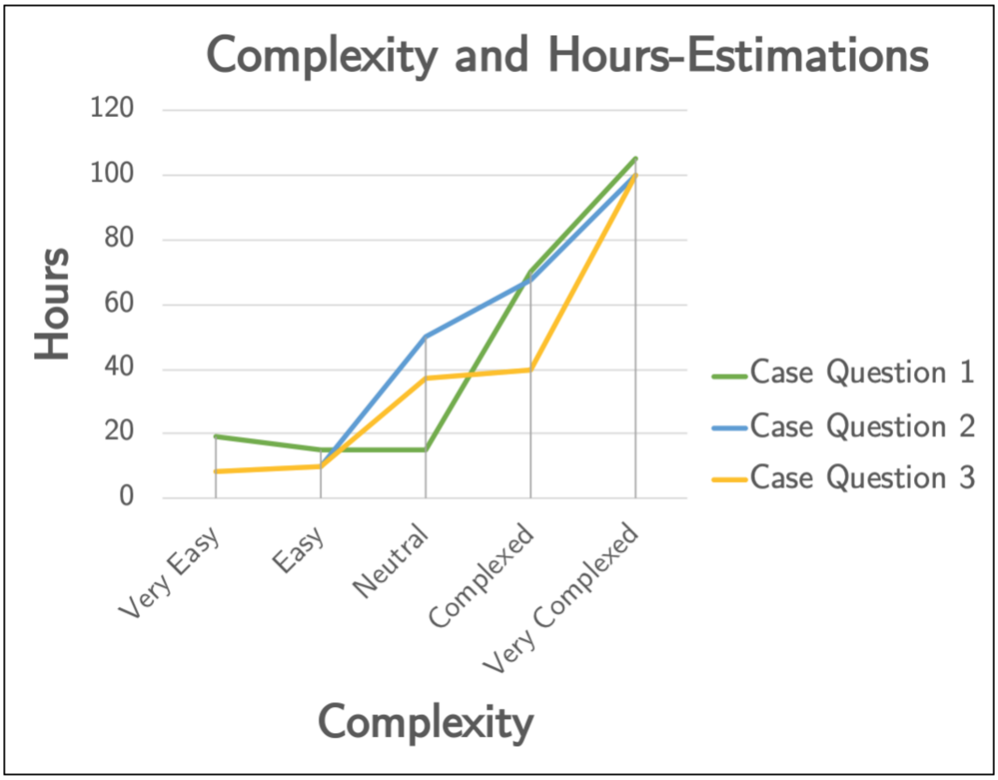

Figure 6.10. Case Questions and Complexity - Median values used for hours

Comparing complexity towards the estimations of hours, the graph shows a higher estimate of hours when the perception of complexity rises for CQ1, CQ2 and CQ3. CQ1 has a little opposite trend from *very easy* towards *neutral*, but the difference in hours is insignificant compared to the remaining slope. Figure 6.11 shows the complexity data sample used in figure 6.10 for CQ2 from the 13 respondent SEs.

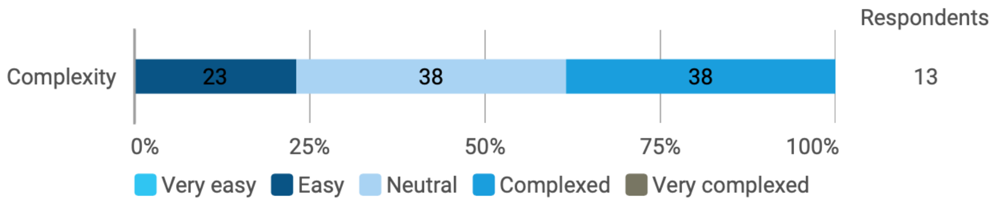

Figure 6.11. Complexity CQ2 - SE only

Work Experience and Prerequisite Knowledge

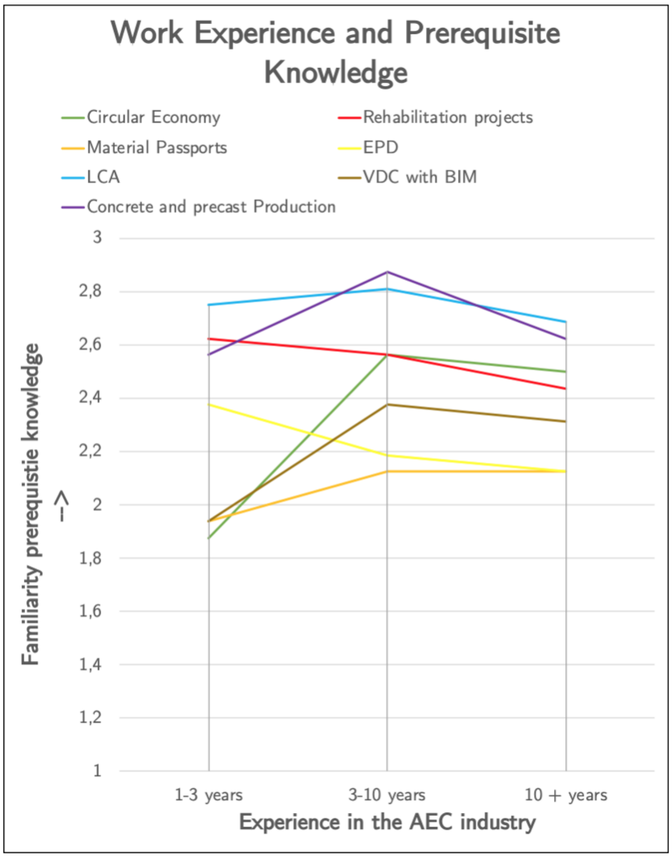

Figure 6.12. Work Experience and Prerequisite Knowledge

The graph in figure 6.12 shows the relation between prerequisite knowledge and the respondents´ work experience. Surprisingly, respondents with *3-10 years´* experience state more knowledge than *10+ years* on all topics except *MPs* where the familiarity is even. Further, the data shows that the respondents with the least experience (*1-3 years)* claim the highest familiarity with *rehabilitation project*. The same group also has the least knowledge of both *CE*, *MPs VDC with BIM*, even so, they are fresh out of campus, where the more academic term VDC should be more common.

Case Question´s Hours-Estimation and Prerequisite Knowledge

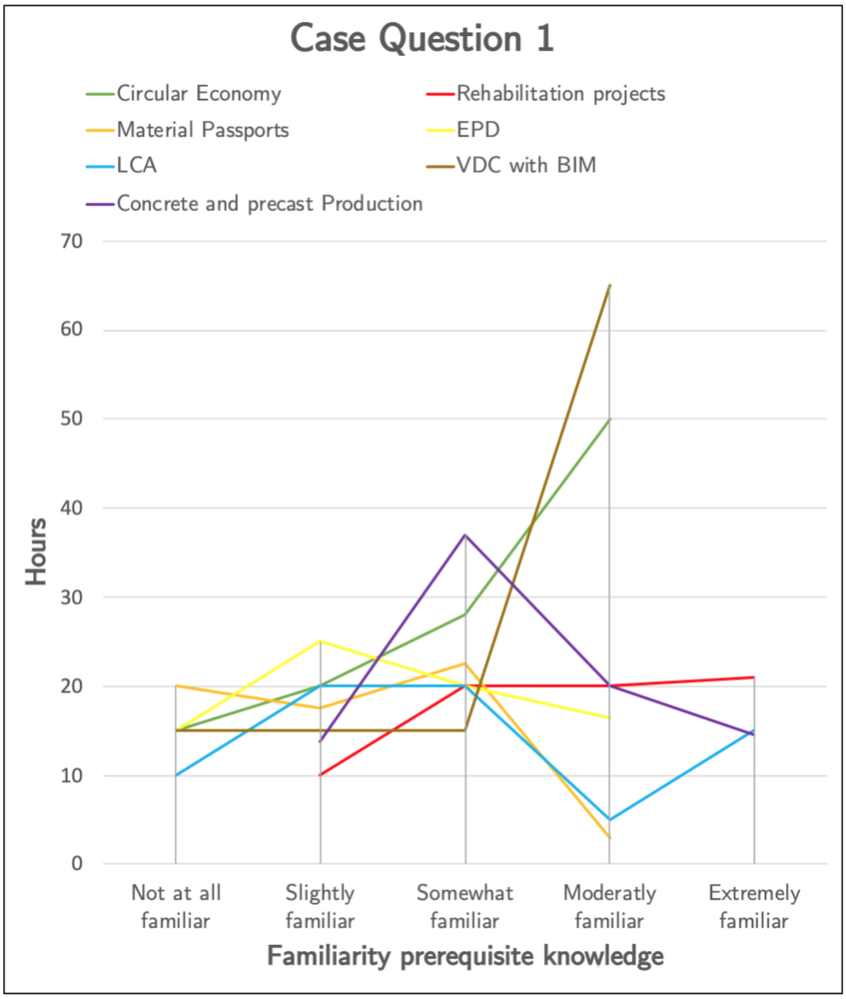

Figure 6.13. Case Questions and Prerequisite Knowledge - CQ1 - Median values

Scrutinizing figure 6.13 give outputs for hours estimations connected to CQ1. The purple and red line shows a trend that those who are well known with both *rehabilitation projects* and *concrete and precast production* gives low estimates, between 15-25 hours. Respondents well known with *LCA* also give low estimates. The highest estimates come from the group that are *moderately familiar VDC with BIM* and *CE*. The relatively big difference in hours between *CE* and *MP* could indicate that those who are moderately familiar with these two topics are different respondents. Also, figure 6.2 shows that the *moderately familiar* for these two topics only represent 8% off the respondent, where outliers (if used) would have cut these out).

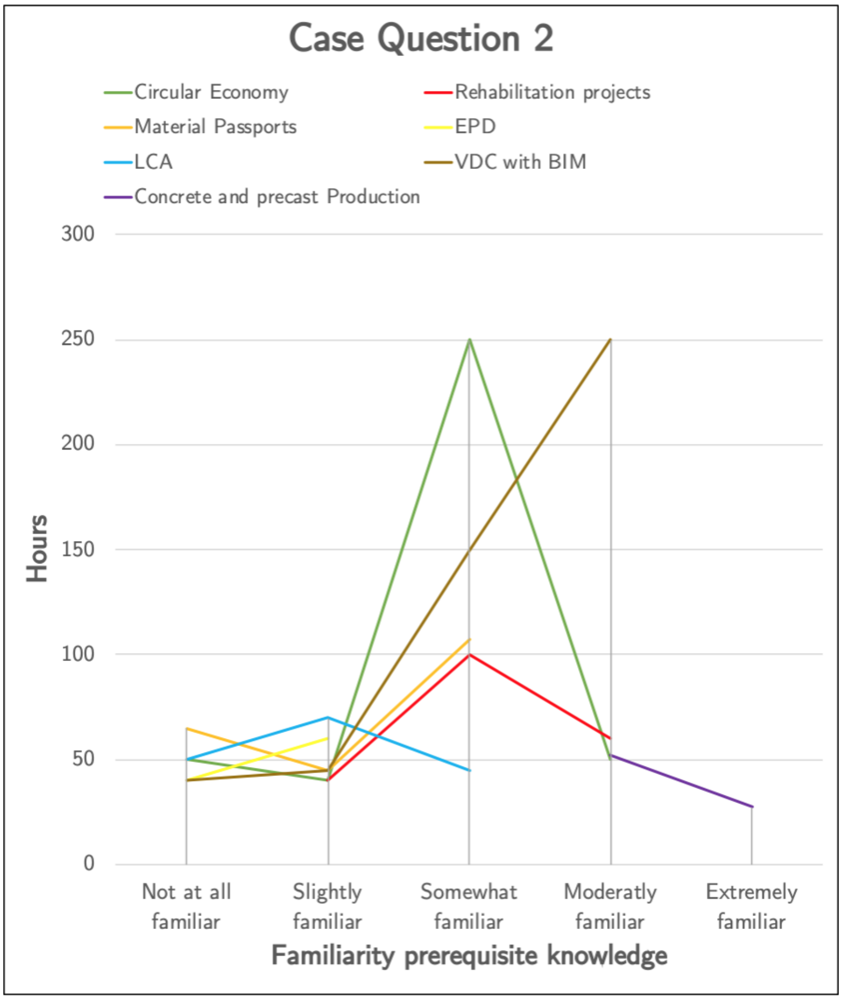

Figure 6.14. Case Questions and Prerequisite Knowledge - CQ2 - Median values

Respondents *moderately and extremely familiar* with *concrete and precast productions* gives the lowest estimates for CQ2. This alone indicates that the median calculated for CQ2 (displayed in table 6.8) into 45 hours might be too high in terms of required manpower. Removing the outliers for CQ2 gives a new median on 40 hours and a mean on 52 hours. This would indicate removal of all estimates over 158 hours, which is those respondents who are *somewhat familiar* with *CE* and *moderately familiar* with *VDC with BIM*, which makes up for 5% and 5% of the respondents, see figure 6.6.

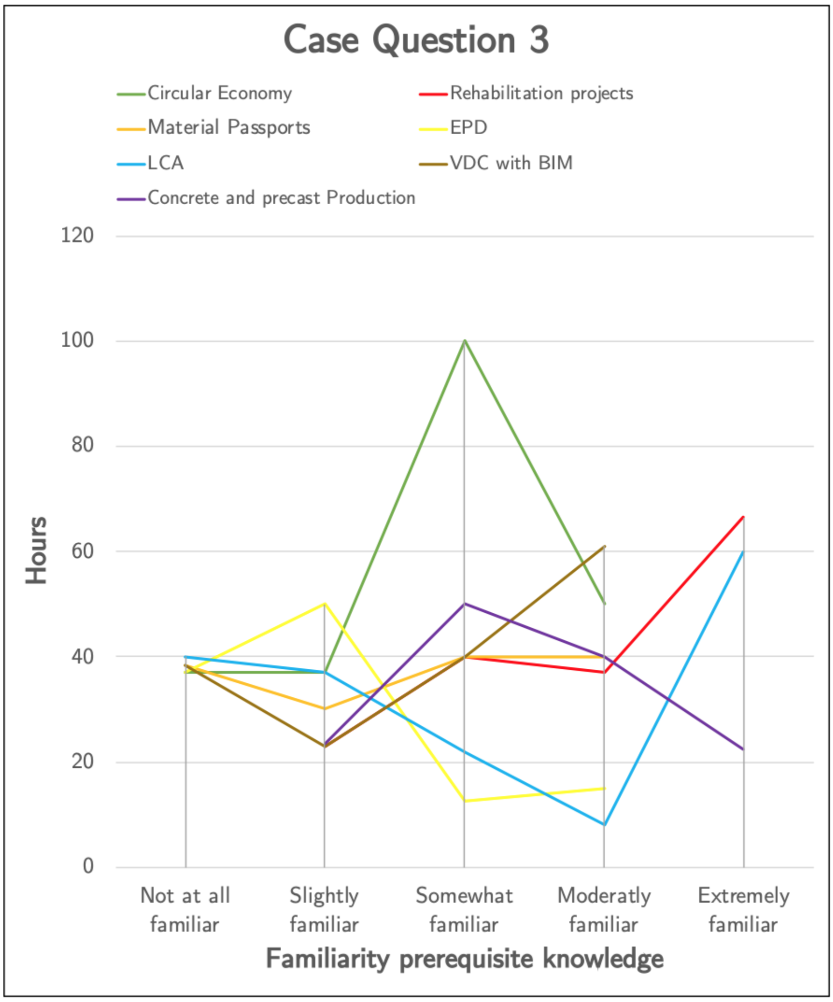

Figure 6.15. Case Questions and Prerequisite Knowledge - CQ3 - Median values

Outputs from CQ3 are as CQ2 also affected by not removing outliers, when looking at *CE*, Looking into. From figure 6.2, one can see that 35% are *not at all familiar*, 40% *slightly familiar*, 17% *somewhat familiar*, and the remaining 8% are *moderately familiar* with *VDC with BIM*, which makes it difficult to conclude on anything form the brown curve in figure 6.15. CQ3 in relation with *VDC with BIM* is therefore investigated further with figure 6.18 in section 6.2.2. The same goes for *EPD* and *MP*.

Case Question´s Complexity and Prerequisite Knowledge

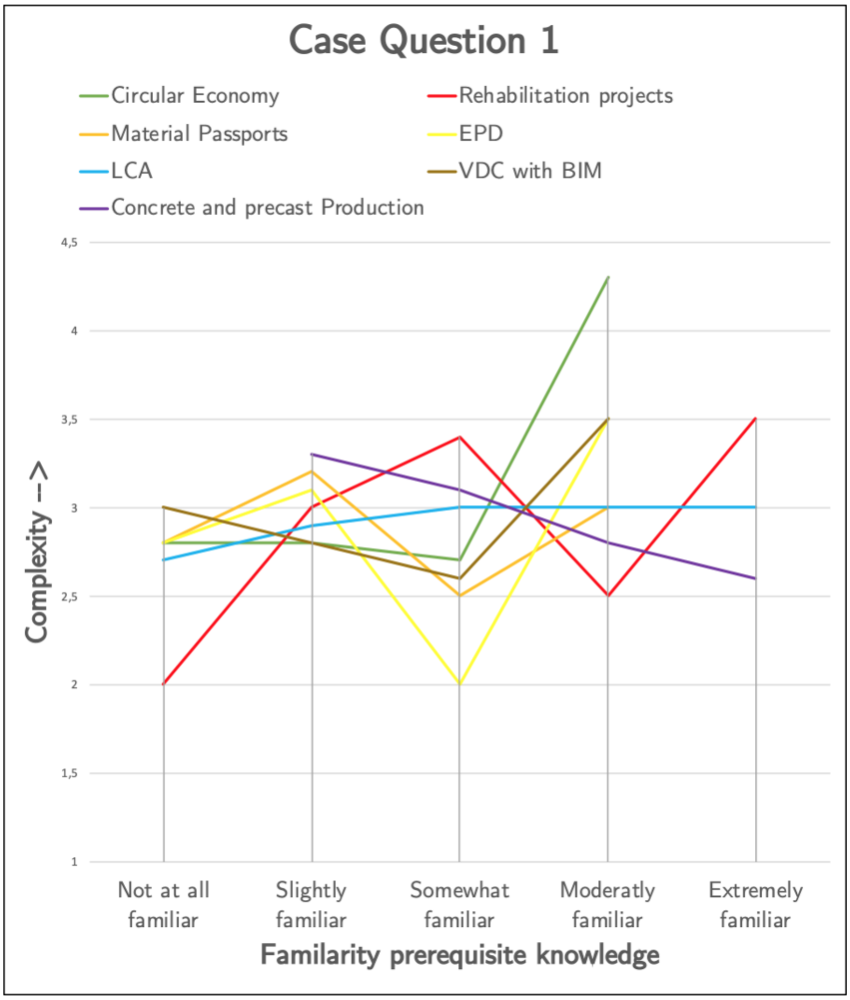

Figure 6.16. Complexity and Prerequisite Knowledge - CQ1Median values

Looking into *concrete and precast production* for CQ1, the higher the familiarity, the lower the complexity. This could imply that those who work directly with precast elements indicate that investigating the health/condition of the element has a neutral difficulty, hence the complexity score of 2.6. Those who are most familiar with *rehabilitation projects* indicates the operation to be more complex than *concrete and precast production*, with a complexity score on 3.5. Respondents who are *moderately familiar* with *CE* states the highest complexity for CQ1, with a complexity score of 4.3. Figure 6.3 tells us that that the percentage of respondents *moderately familiar* with *CE* is very low, indicating that the complexity-score on 4.3 for *CE* could be lightweight. Scrutinizing the *LCA*-curve shows us a steady complexity-score through all levels of familiarity. This indicates that those who are used to, and not used to working with material health of a product through its life-cycle, give the same complexity-score, a score overall relatively close to *concrete and precast production*.

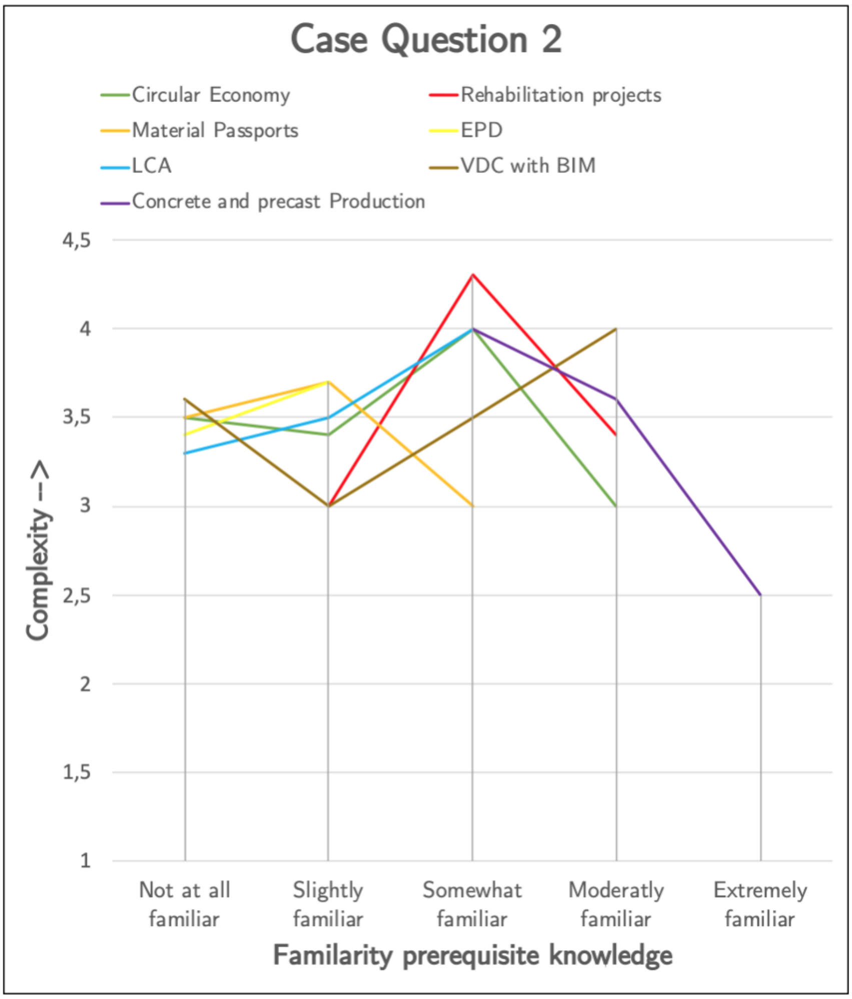

Figure 6.17. Complexity and Prerequisite Knowledge - CQ2 Median values

For CQ2, where only data from SEs are included, those who are *extremely familiar* with *concrete and precast construction* says that the operation is neither *very complex* nor *very easy*, with a complexity-score of 2.5. Those who are familiar with *MP*s shows a decreasing complexity as the knowledge level increases, but no SEs stated a higher familiarity than *somewhat familiar*, meaning it is hard to grasp anything reliable from this. Further, figure 6.6 also shows that 16% of the respondents see themselves as *moderately familiar* with *MP*, which is the highest familiarly rate with *MP*. The overall complexity-score for *rehabilitation project* were 3.6, where the *moderately familiar* (highest familiarity level and stood for 37% of the respondents) gave the operation in CQ2 a complexity-score of 3.4.

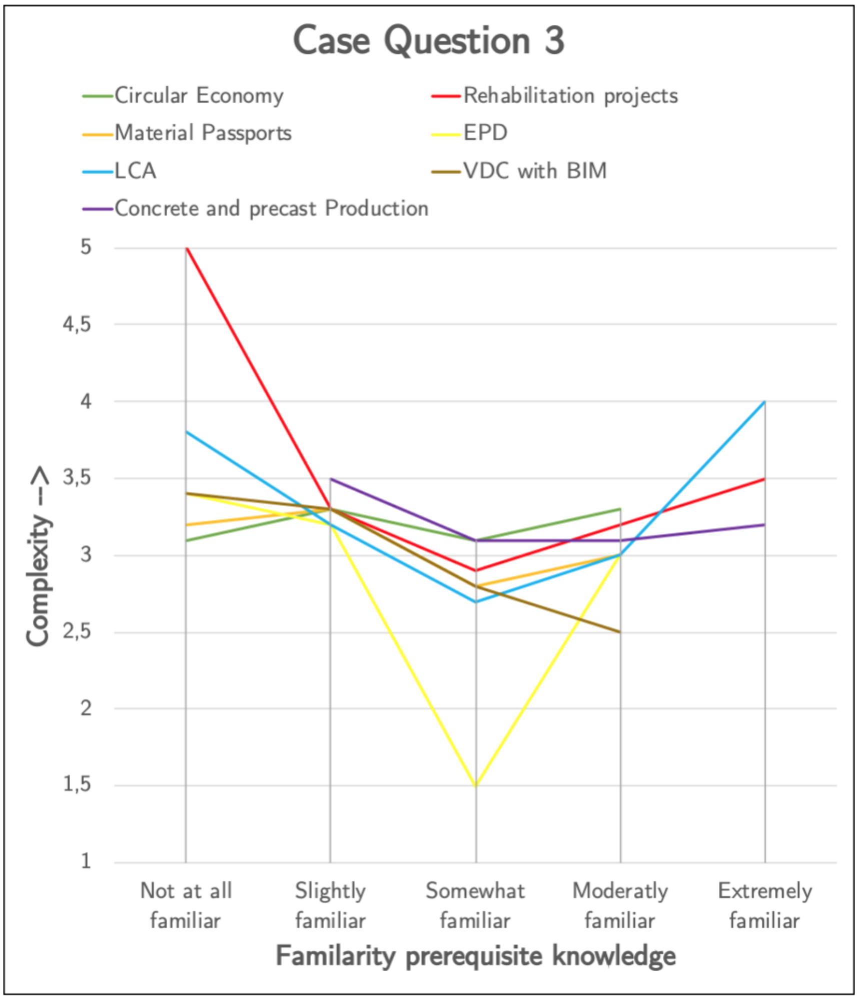

Figure 6.18. Complexity and Prerequisite Knowledge - CQ3

For CQ3, the graph displays a trend where familiarity with *VDC with BIM* increases, the lower the complexity gets, with the complexity-score going from 3.3 to 2.5. Also notable is the similar pattern with MP, only with a smaller difference in the curve. The only topic which is lower in complexity at *not at all familiar* than at *extremely familiar* is LCA. Those who work with components through its life-cycle state a high difficulty with modelling the elements correct. The percentage of the respondents with the highest knowledge upon *LCA* accounts for 2% for the respondents, while *moderately familiar* accounts for 6% of the respondents and *somewhat familiar* with 29%. Thus, the complexity-score more towards the centre of the familiarity-scale could be more representative towards a reliable result for *LCA*.

Case Question´s Complexity and Experience

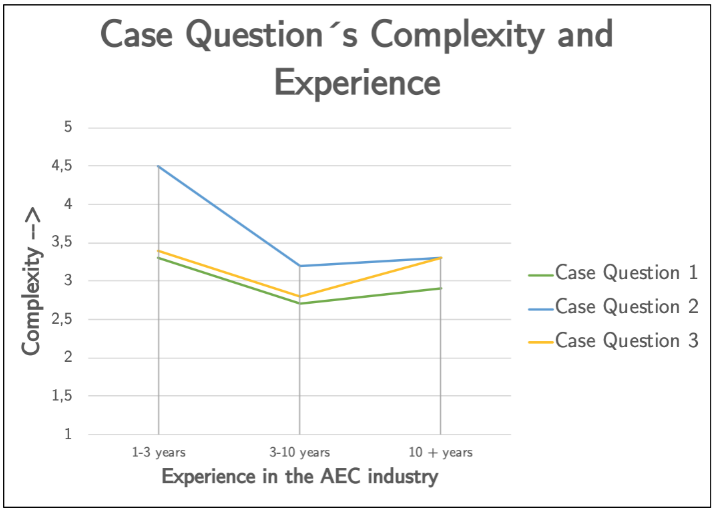

Figure 6.19. Complexity and Experience

All three case questions have similar curves when comparing experience and grade of complexity. As the graph displays, respondents with the least experience claim the highest estimates of complexity, with respondents with *3-10 years* stating the lowest complexity for all three questions. All case questions show an increase in complexity from *3-10 years* towards with *10 + years*, with CQ3 having the biggest difference between *3-10 years* and *10+ years*.

Case Question´s Hours-Estimation and Experience

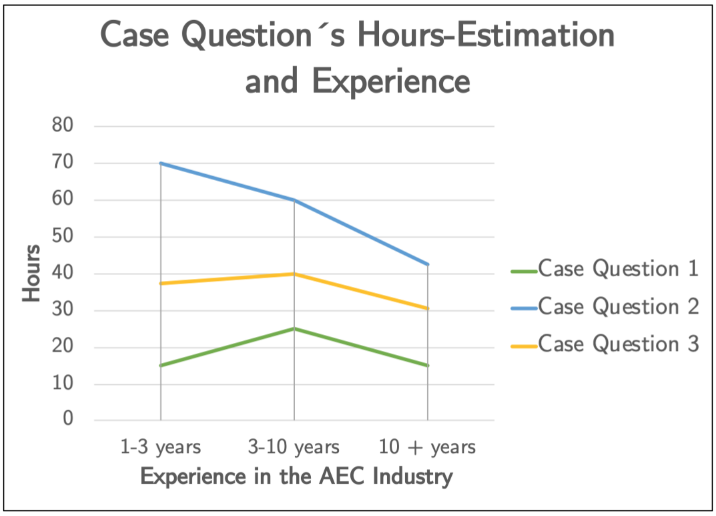

Figure 6.20. Case Questions and Experience - Median values used for hours

When comparing hours-estimation and experience, both CQ1 and CQ3 shows the same trend where the *3-10 years*-group gives the highest estimate. For CQ2, the estimated number of hours for the operation decreases rapidly as the respondents´ experience elevates.

6.3 Analysis Summary

6.3.1 Prerequisite Knowledge

Topic	**Familiarity-score (1-5)**
Circular Economy	2.6
Rehabilitation projects	2.9
Material Passports	2.4
EPD	2.5
LCA	2.6
VDC with BIM	2.6
Concrete and precast production	3.1

Table 6.9. Familiarity-score prerequisite knowledge in a five point scale where 1 = *Not at all familiar* and 5 = *extremely familiar*

The Investigation Process - CQ1

CQ1 had the purpose to enlighten necessary manpower and complexity towards investigating the condition/health of the precast elements. The median for step one where 17.5 hours and the total complexity-score were 2.9 (neutral).

The Data & Calculation Process - CQ2

CQ2 had the purpose to enlighten necessary manpower and complexity towards investigating, gathering, and calculating structural data. The median for step two were 45 hours, with a total complexity-score of 3.2 (complex). Note that 40 hours was found as a more realistic estimate, see figure 6.14 section 6.2.2

The Modelling Process - CQ3

CQ3 had the purpose to enlighten necessary manpower and complexity towards modelling the case building´s structural model down to a material level. The median for step three were 37.5 hours, with a total complexity-score of 3.2 (complex).

7 | Discussion

This discussion first debates MP-matters other than what the survey comprehended before the competency and resources are discussed in general. Lastly, the discussion is structured after the three-way path towards mapping existing buildings as material banks;

- The investigation process - CQ1
- The calculation process - CQ2
- The modelling process - CQ3

where the intention is to bring together data and information from the initial analysis (chapter 3), the analysis (6) together with the problem statement: *How can the methods of mapping existing buildings as material banks be done more efficiently?*

7.1 The Full Extent of a Best Practice Material Passport

The survey comprehended information regarding the collection of structural data and data concerning the health/condition of the elements. However, table 3.2 which describes what Heinrich and Lang [2019] suggested as necessary information and data for a best practice MP, displays a lot more information than what the survey covered. Most of the LCI is left out, with the survey emphasizing **physical →structural data** from table 3.2. The student found this necessary in order to keep the survey within a reasonable context and time for the respondents. CQ2 did ask to calculate and determine information the respondents find necessary for reusing the precast elements; "*The investigation should result into enough information you would find necessary for reusing the elements.*". Thus, were this the only opportunity for respondents with some prerequisite knowledge about MP and LCI to enlighten their knowledge.

The student had a preconception that the overall familiarity with MP was as a little higher than what was found. In the aftermath, recognising the somewhat mediocre familiarity, one can presume that respondents may have accounted for less information needed to be collected from the case building than suggested by than Heinrich and Lang [2019] in table 3.2 than what the student originally thought. If the respondents, in general, where "far away" from a best practice MP, this could indicate that the overall results in terms of both complexity and hours-estimate for both CQ1, CQ2, CQ3 may be wrong.

Figure 7.1 debunks this issue. When comparing familiarity towards hours-estimations for the different case questions and singling out familiarity towards MP, the differences seem

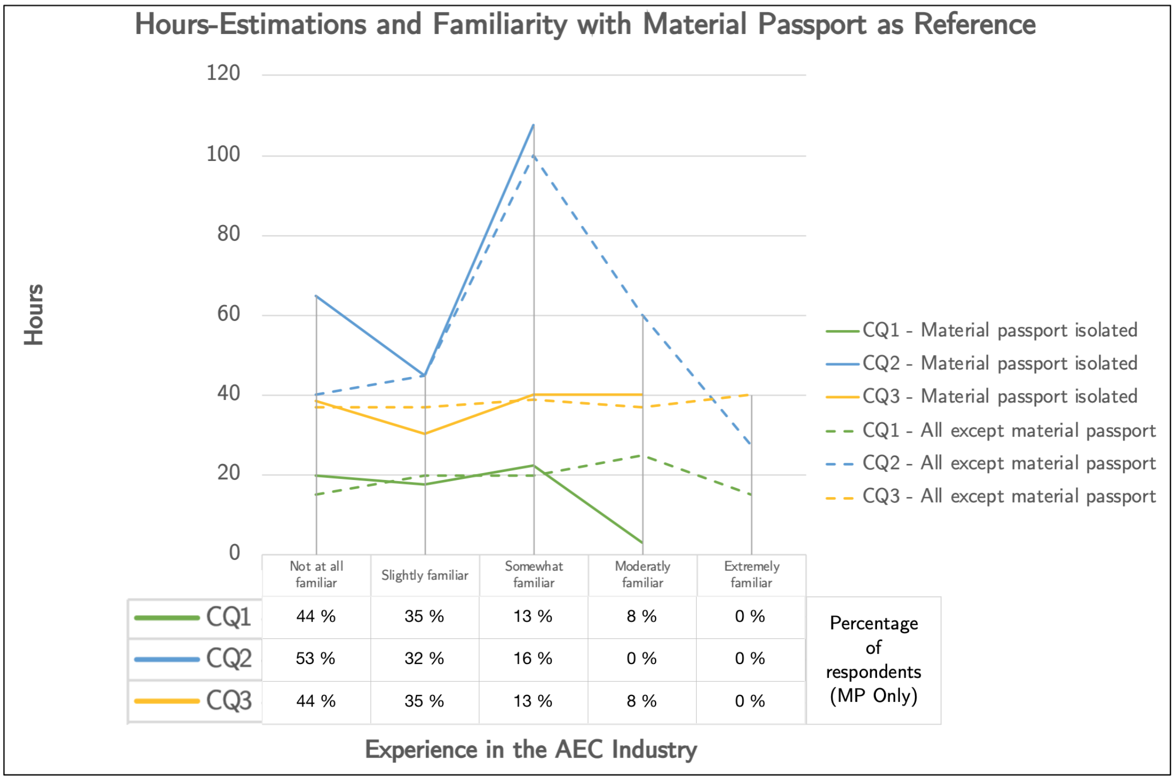

Figure 7.1. Hours-Estimations and Familiarity with MP as Reference

insignificant. Only for CQ1 the two green lines separate path significantly, where MP isolated (whole green line) actually gives lower hour-estimates than non-MP.

7.2 General Thoughts - Competency and Resources

7.2.1 Competency

The analysis showed a below familiar-trend in the AEC industry, towards the "eco-topics", see table 6.9. CE, MP, EPD, and LCA all were between 2.4 and 2.6 within the five-point scale of familiarity. When comparing those numbers to the *concrete and precast production* that has a score of 3.1, knowing that a little under half of the respondents are SEs, the student sees a need, but not an urgent need in increasing knowledge around these topics. The somewhat lower score could also be explained the indications of broad use of trivial-names, see section 6.2.2. Even so, the overall knowledge of sustainability topics is not convincing.

7.2.2 Resources

Adding up the median hours-estimations (17.5+45+37.5) for all three operations indicates that the total need of manpower for mapping the case building´s precast elements into MPs to serve as material banks is 100 hours. If that number is multiplied with the average hour-cost for a consultant engineer, the total sum will be pretty high for mapping *only* the precast elements of a two-story building. Also, one would most certainly want to map larger buildings than the case building, making the cost even bigger. Creating buildings into material banks would also be a part of the total cost, hence there is a cost for procedures like extracting deconstruction, refurbish and fitting, and construction, among others.

The required resources of 100 hours for a two-story 300 m^2 buildings shows that whatever a building is chosen, the building should be highly relevant for urban mining. Mapping a building which is fully operational and sustainable in its current function should perhaps not be mapped into material banks, at least not be prioritized.

7.3 Locating Areas for Improvement

This section discusses the different results with belonging analysis, with the purpose of locating what those out of the three-step path have the biggest room for improvements.

7.3.1 The Investigation Process - CQ1

Requiring the leas resource, the data collected for step one argues that the investigation process has the least need for improvements of the three steps. As the analysis showed, CQ1 had a median on 17.5 hours with a 2.9 complexity-score, the lowest in complexity and hour-estimations. Figure 6.13 and 6.16 in the analysis showed low estimates with complexity and hours for those moderately to extremely familiar with concrete and precast production.

However, even seemingly being a straightforward task, there are some factors that could change the necessary resources to complete the step. The question´s belonging operation was to investigate and inspect the health/condition of the precast elements. Different buildings vary in form depending on several factors like architecture, construction date, quality, technique, among others. Thus, the precast elements could be covered by e.g. plaster, ceiling, painting, wooden floor, insulation, which makes it hard to investigate the precast elements, as these items could hinder the visualization of the elements. Therefore, the data on 17.5 hours and a neutral complexity-degree only works as an indicator due to buildings being different. Even so, figure 6.7 illustrates that most of the estimates are between 60 and down to 1 hour, meaning somewhere between those numbers is realistic. The “case-building” also was intended as a simple small building with the purpose of leaving little room for creativity for each respondent, keeping a joint perception of the operation. Thus, the student sees step one, the investigation process to be the least critical method to improve in terms of required resources.

7.3.2 The Calculation Process - CQ2

With a median on 45 hours and a complexity-score of 3.2, step three (CQ2) requires the most resources according to the AEC industry of three found steps in this thesis. The complexity-score is equal to step three (CQ3) and has a 0.3 differential towards CQ1. In hours, the differential was 27, demonstrating this is the most time-consuming operation overall. Further, as the analysis showed in figure 6.14, those with a familiarity-score higher than 3 gave the lowest estimate, solidifying this statement. This makes sense from theory highlighted in section 3.4.1 and 3.3.1, looking into what data and information are necessary to produce, based upon Addis [2012] proposed method to investigate and calculate for information on the precast elements to receive data that Heinrich and Lang [2019] state is necessary for the best practice MP, see table 3.2 and 3.3. It is, therefore, safe to say that one needs to make the process as efficient as possible and that there is room for improvement in *step two*.

7.3.3 The Modelling Process - CQ3

With the same complexity-score as CQ2, step three (CQ3) requires the second most resources and was considered as a complex operation (3.2 out of five). This indicates as with step two that the operation is more of a time-consuming job than what it is complex. Figure 6.18 in the analysis also showed that the complexity-score decreases with an increasing familiarity with VDC and BIM, reaffirming this statement. The same group also gave some of the highest hours-estimation, see figure 6.15. The data also to some degree confirms what Honic [2019] in section 3.5.3 states, where one of the biggest challenges was the obligate use of predefined materials and non-consistent ways of parametrization. Kovacic and Honic [2019] also highlighted the need for extra manpower with prerequisite knowledge related to sustainability. The data-sample upon prerequisite as mentioned earlier in this chapter was not convincingly sound, see figure 7.2. Thus, *step three*, the modelling-operation seems to have room for improvement, confirmed by both Kovacic and Honic [2019] and this thesis.

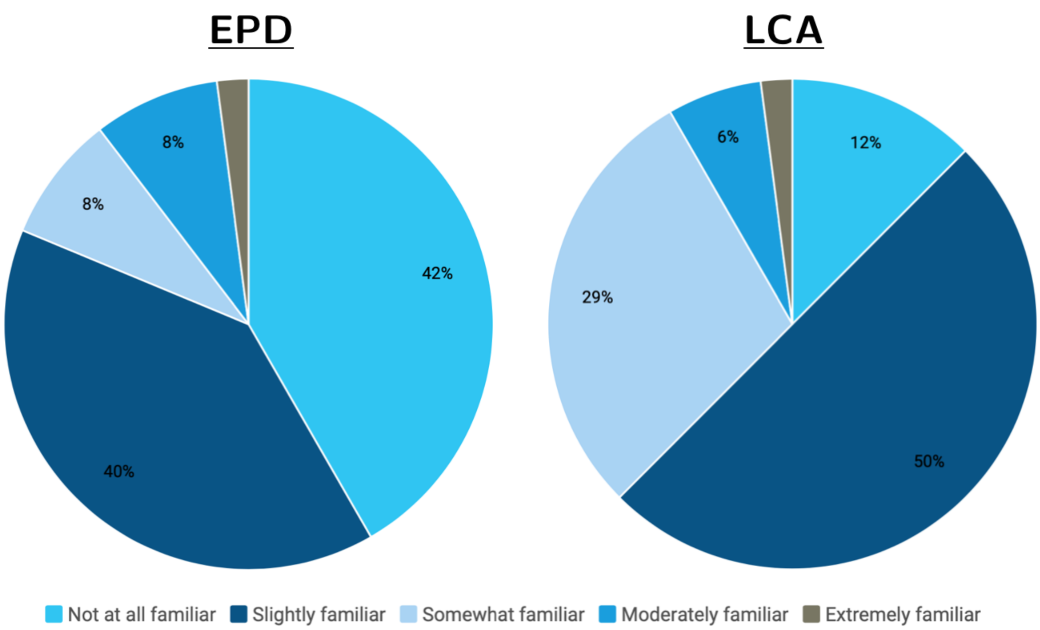

Figure 7.2. Familiarity for EPD and LCA

7.4 Specifying What to Improve

Step two (CQ2) and step three (CQ3) were found to have the most room and need for improvement. Thus, step one (CQ1) will not be discussed in this section. Both steps had a neutral complexity (3.2 out of 5). Further, figure 6.18, 6.17 and 6.19 showed that overall, the higher familiarity and/ experience, the lower the complexity. This indicates that it is not necessarily missing technology or lack of knowledge being the main obstacle for mapping existing buildings as material banks. Thus, this section will continue investigating where necessary resources (hours) could be reduced, and not what technologies could help.

7.4.1 The Data & Calculation Process - CQ2

Addis [2012] presents the following steps towards determinng some of the structural data required in the best practice MP suggested by Heinrich and Lang [2019]; *scrutinize original project material, put use of the past design codes used at the date of construction, physical investigation, X-ray and scanning technologies* (also presented in section 3.4.1).

Scrutinizing original project material is an inconsistent way of getting to necessary data for the structural elements, due to the fact that there is no guarantee that such information actually exists for old buildings. However, if the original project material exists, it would probably be the most efficient way of sampling and calculating necessary structural data [Addis, 2012]. The **use of past design codes** could give some information but is dependent on regulations and laws connected to those design codes and by so to what degree they were actually used. Design codes alone will not give all the necessary information either but could help make it more efficient when combined as support with the other alternatives presented by Addis [2012]. **Physical investigation** of the building and precast elements, like removing some of the concrete to collect information about reinforcement steel dimensions and concrete cover, can somewhat be seen as a sluggish way of getting the information. One could argue that **X-ray and scanning** off the precast elements is the most efficient of those two, and if precise enough it could tell aggregate details Addis [2012]. Such a method could also have an effect on making step 1 (CQ1) more efficient.

To sum up step two (CQ2), it seems like it is not about making the methods itself more efficient. With several techniques towards sampling sufficient information, stage two seems to be about ensuring that the most efficient methods are available, and not improving the methods themselves. Further, making step two (CQ2) more efficient is dependent on the outcome step one CQ1. Let say the precast elements in a building were all in good condition, the fastest way to calculate and determine data was if the elements where similar so that principles within economic of scale could be applied to the mapping process. If all the precast elements were homogeneous, the mapping process would be truly more efficient, hence the same workflow and numbers for one element could be applied for the next. Several studies have proven economic of scale within the industry to be highly positive, where Gottlieb and Haugbølle [2010] found that the effect of repetitiveness in the AEC industry (homogeneous tasks) could reduce the overall budget of construction projects with 6-12%.

7.4.2 The Modelling Process - CQ3

For step three (CQ1), specifying what to improve approach from the challenges presented by Kovacic and Honic [2019] in section 3.5.3:

- Inconsistent nomenclature, making the process semi-automated.
- Predefined elements limits designers
- Need for extra manpower
  - The need for extra manpower will not be discussed further in this chapter, as it is the overall goal for this thesis with its problem statement to reduce.
- No consistent way of parametrization

Inconsistent nomenclature in the different LCI increases the number of manual operations and hinders the modelling process towards full automation [Kovacic and Honic, 2019]. When the overall goal is to reduce hours spent on modelling and information handling, proceeding towards automation can be considered crucial. An increasing in level of automation would lessen the need for resources significantly. For existing buildings, it is reasonable to understand that the need for a consistent nomenclature might be bigger, hence there needs to be a joint understatement and establishment of nomenclatures for the building components in order to work truly efficient between users and databases [Volk et al., 2014].

Predefined elements limiting designers is a challenge when creating MPs for new buildings. For existing buildings, elements are already defined, meaning there are few to none possibilities changing the elements. Thus, elements in existing buildings do not limit designers, hence the elements are what they are. This does not advocate for existing buildings to be a better fit for MPs, it rather states that the challenge with designer´s freedom is non-existing due to the elements already are designed, built, and dispatched. One could, therefore, say that this problem where designers are limited is maximized to a level where it would cost too much both energy and monetarily to do otherwise, and is therefore non-existing.

No consistent way of parametrization, making it MIAT necessary bringing together the elements with properties, LCI and the BIM-environment. There are commonly two ways of parametrization with LCI [Antóna and Díazak, 2014]:

1. An LCA tool extracts information from the BIM-environment and combines the information with LCI.
2. Environmental properties included in the BIM-environment attached as the BIM-object´s properties.

For the **1. alternative** to fit existing buildings, there must exist LCI for materials in use. Using the same time horizon as of the case building tells that there must exist LCI in these databases older than 40+ years. Several LCI-databases exists, both international and national. Doing quick research in some databases like *GaBi* (international), *EPD-Norge*, and *EPD Danmark*, information on materials and products 40+ years old does not exist. The **2. alternative** would work with existing buildings, hence information could be added as proprieties inside the BIM-environment when modelling if the LCI is available for the designer. This would indicate manual entries for every unique element in the model, where the number of entries varies with the level of granularity. Variation in granularity also makes the LCA more difficult, hence the model´s inconsistency. Thus, there needs to be a set level of granularity for the elements in a model, so that designers can extract desired information knowing it will be there and be sufficient [Röck et al., 2018]. Therefore, a lot of time would be consumed for modelling due to the high structure and material variety in the elements combined with necessary granularity for each element.

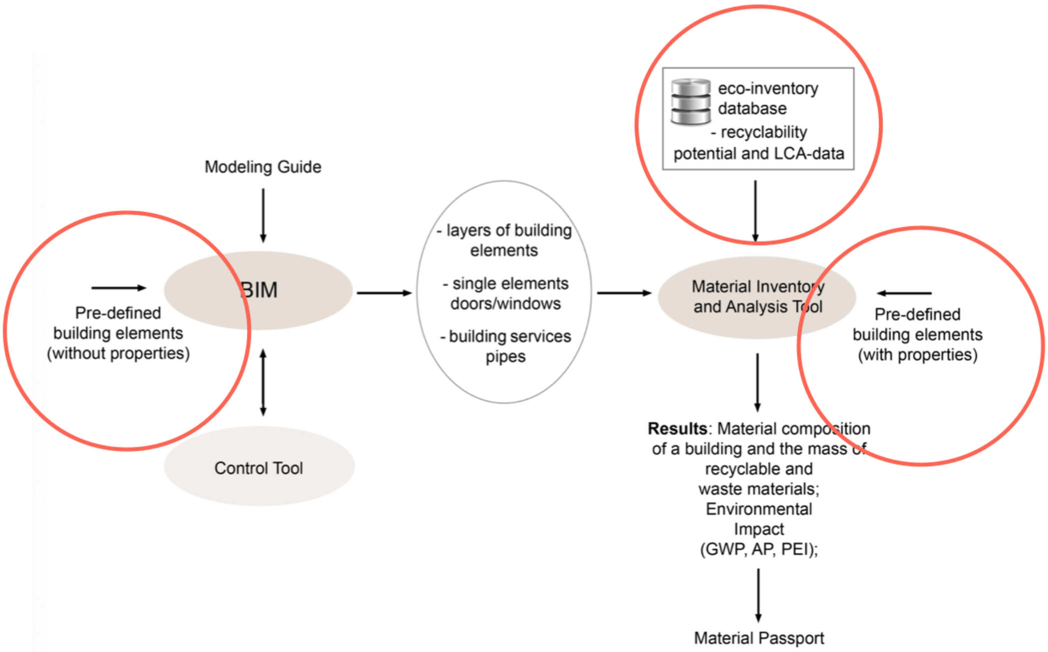

Figure 7.3. Specific areas to make more efficient when modelling existing buildings (remake from figure 3.10)

There are more issues that could "slow" down the modelling-process other than the challenges presented by Kovacic and Honic [2019]. As mentioned Honic et al. [2019a] used predefined elements in their model for BIM-based MP, where for existing buildings the elements already exist. Thus, the entire process of modelling BIM-based MPs will probably require even more manual operations than with new buildings, which is understood off by the high hour-estimates from respondents for the case building. Every unique structural ability/information towards the precast elements, see section 7.4.1, needs to be described in the BIM-environment. This indicates that a solution to make step three more efficient is to hit general parameters for most of the buildings chosen to be mapped as material banks so that every manual entry conducted decreases the number of manual entries in the future.

7.5 Step Two and Three Junction

This chapter so far has highlighted the need for improvements in specific areas and procedures for making the mapping of existing buildings as material banks more efficient. From step two, the calculation process (CQ2), scrutinizing original project material combined with X-rays and terrestrial scanning seem to be the best alternatives. Thus, measures should be done so that whoever is mapping has the freedom to choose the most efficient methods. Similarities between elements in a building and/or several buildings could help. If buildings are constructed with similar techniques, styles, etc. and at the same time, one could argue that there is some common and shared information between buildings. Thus, investigating for a generalised precast element production could help reduce the required resources, hence contributing to possible missing project material.

Making step three the modelling process (CQ3) more efficient is all about automation. Unfortunately, the level of automation is probably lower for existing buildings than new ones. The reasons are among other the lack of LCI for old building materials and that there are no samples of predefined elements for these old buildings, hence one does not know how the elements appearance before choosing a building and conducting step 1 (CQ1) and two (CQ2). Thus, the more equal and similar elements are, previously inputs for one element could reduce manual inputs for a new element, implying a more efficient modelling approach alongside fitting the criteria and method for a BIM-based MP proposed by Honic et al. [2019a].

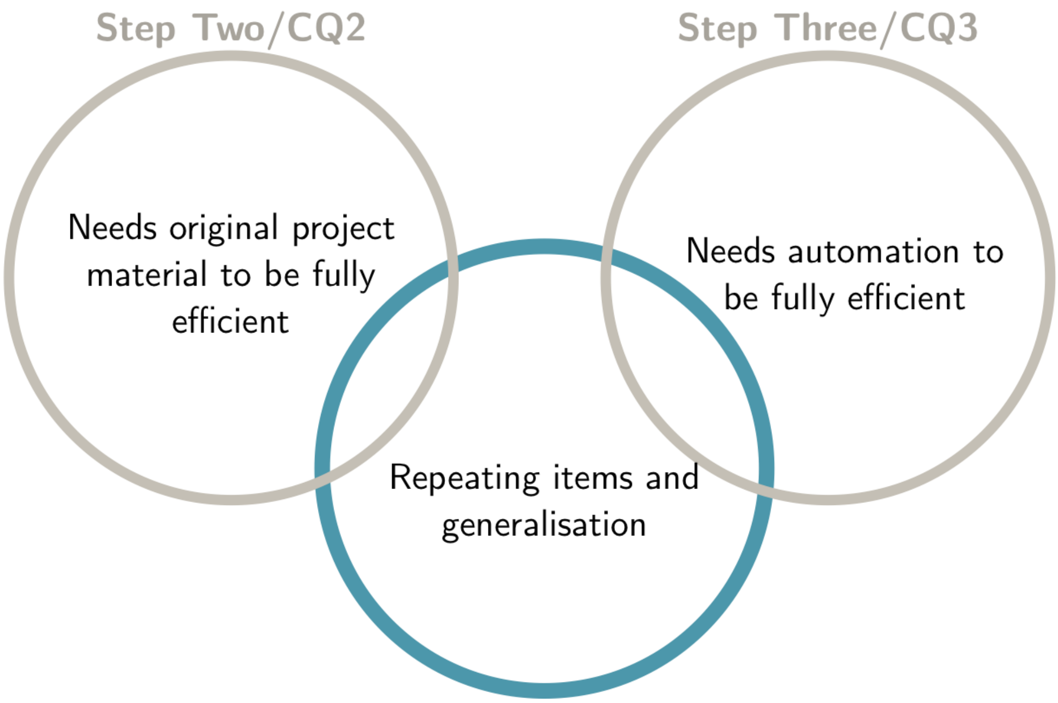

Figure 7.4. Need-junction for step two and three

Common for both step two and three, they both need a vast generalization and repetition to be as efficient as possible, as figure 7.4 illustrates. It was also found that for all three steps, the required resources for mapping a building demonstrates the importance of a building´s high relevancy towards urban mining, with the precast elements in the case building costing 100 man-hours. Therefore, the student going forward does not approach how the methods itself can be done more efficiently. The solution towards a more efficient mapping of existing buildings should rather comprehend measures ensuring that the most efficient paths for mapping are available. Phrasing it differently; instead of the methods being optimized for buildings, can the buildings optimize the methods?

8 Suggested Solution

The discussion ended by asking what the existing building stock can do to optimise the methods for mapping buildings. How can the steps towards existing buildings as material banks be more efficient, and how to secure the buildings´ relevancy for urban mining? Needless to say, built buildings are what they are. However, through the vast diversity of buildings constructed through time, some buildings grasp together on common ground, sharing a unity in the land of diversity. This suggested solution seeks to find this common ground of unity and generalization between buildings that hopefully can ease the mapping of existing buildings into material banks.

Note that this solution follows the thematic framework of this report, see section 2.3.6, and will, therefore, comprehend precast elements and the bearing elements for a building. The solution itself is not tested nor proven, it is erected upon needs found in this thesis, complemented with the student´s knowledge on what seems to be a reasonable approach towards covering these needs.

8.1 Concept

The suggested solution´s main concept is a strategical and careful selection of buildings to map as material banks. Section 7.5 showed an urgency for a tool to identify buildings with the highest degree of reusable generalized homogeneous items. The tool should therefore by the student´s perception identify repetitive buildings based upon the idea that a higher degree of repetitiveness, the more efficient mapping of existing buildings as a result of:

- Buildings can share LCI and make parametrization more consistent if elements are composed with the same material structure and only differs in size so LCI can be added and transferred on a component level.
- Increase the level of automation if nomenclature created for one building can be shared and transferred with minimal adjustment, due to a high degree repetitiveness within components, elements, and materials.
- The higher the similarity between buildings, the more similar design. A more similar design could imply that that the same design codes, techniques, etc. were applied, ensuring that a certain degree of information exists for buildings, and can be transferred between buildings.

This suggested solution presents the student´s self-made concept for such a tool, inspired by Heinrich and Lang [2019] and *life cycle management*, called *Repetitive and Relevancy Component Analysis (RCA)*, see section 3.3.2. The RCA has two main objectives:

1. Quantify qualitative and quantitative data to determine a *Repetitive and Relevancy score (R-Score)*, see equation in figure 8.2.
2. Create a template for identifying "the next building" to ensure repetitiveness, see figure 8.1

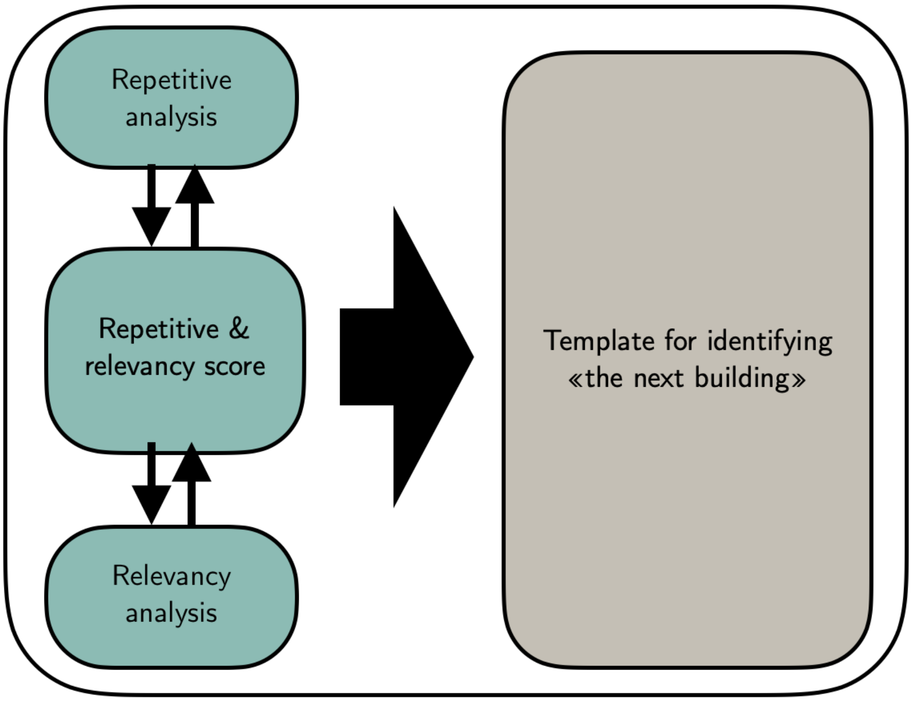

Figure 8.1. RCA, adopted from figure 3.7

This thesis´s problem statement was to increase the mapping of existing buildings as material banks more efficient. By mapping a building with a high R-Score, the first elements and components in the buildings would require the same amount of resources "as always". However, the purpose is not to reduce the required resources for these elements. The purpose of the R-Score is rather reducing time spent on the next element, next component thereafter the next building. Thus, finding the R-Score is about breaking buildings into subjects (parameters), so mapping existing buildings can be realised into a more sensible thing and. Figure 8.3 shows how an example of the *Repetitive-Score*-guiding, where a building with a green score should be prioritized before a building with yellow, and red buildings should not be considered for mapping and urban mining. The higher the R-Score, the more efficient step two and three becomes.

8.1.1 The Repetitive Score Equation

The R-Score R_s is given by the student´s proposed equation:

The parameters are further explained and elaborated in section 8.2. Some parameters in the equation are thought to have a bigger significance than what the numerical value when

$$R_s = A_d + \frac{\frac{B_c}{2} + 5E_a + 5B_g - 2C_h}{100}$$

where $0 < R_s < 2$

and $A_d = \frac{V_r}{S(V_t)}$

Variable	Description
R_s	R-Score
A_d	Architectural Style and Design
B_g	Generic Estimate
C_h	Health Grade
D_a	Building Age
E_a	Accessibility Rate
V_r	Volume of repetitive components
V_t	Total volume of components

Figure 8.2. The R-Score equation with parameters

quantified implies. Thus, they need to be multiplied with constants so their impact on the *R-Score* R_s matches their significance. The relationship between the parameters in the equation in figure 8.2 is the student´s suggestion, based upon that:

- *Building age* is important, but the value itself will be unjustifiably much higher than compared to the rest and is therefore divided in half.
- The *health grade* has the lowest grade due to the possibility of re-paring and fixing elements [Addis, 2012] and therefore given **2** as a constant.
- *Accessibility-grade* and the *generic estimate* found equally important due to the needs found in this thesis and therefore given **5** as a constant.

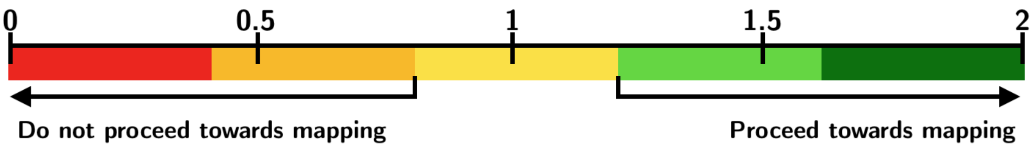

Figure 8.3. Repetitive-score

8.2 Parameters in the Repetitive Component Analysis

The parameters presented in this solution are what the student finds necessary to support the findings in the discussion-chapter. They are all inspired by the best practice MP by Heinrich and Lang [2019] with the purpose of making the RCA a part of the MP. The parameters are sectioned after repetitiveness and urban mining relevancy.

8.2.1 Parameters Towards Repetitiveness

Parameters presented here in section 8.2.1 are connected towards repetitiveness, with the overall purpose to identify buildings who are constructed in a repetitive manner, towards itself and other buildings. In relation to the repetitiveness, the two parameters outlined are:

1. Architectural style and design - A_d

2. Existence of similar buildings- B_g

Architectural Style and Design - A_d

Architectural style and design define buildings historical identity by the use of materials, building-techniques, appearances, among others. Some buildings can be considered extravagant, while others are plain and easy, and built because of an urgent need for housing. Some architectural styles are known for a certain use of material and products and using them in large scales. Figure 8.4 illustrates this, showing a satellite city, consisting of several identical large apartment houses in Oslo, Norway, and symbolizes the repetitive pattern the student chases with this suggested solution.

Figure 8.4. Satellite City, Oslo Norway [Elektro-kontakten.no]

In order to create a quantitative variable for architectural style and design, a somewhat comprehensive investigation is necessary. The architectural style and design - A_d is given by focusing on the building´s percentage of repetitiveness. The suggested approach for a reasonable parameter is given by the student´s proposed equation:

$$A_d = \frac{V_r}{S * V_t}$$

or

$$A_d = \frac{I_r}{S * I_t}$$

where V_t is the total volume of the components, and V_r is the volume of repeating components, I_t is the total number of elements, I_r is the number of repeating elements and S expresses the building´s size. Note that there is a difference between retrievable volume and repetitive volume. As Addis [2012] described, salvaging precast concrete involves cutting/sawing the elements from its connection, meaning some volume is lost.

Building Size - S		
Large	Moderate	Small
1	2	3

Table 8.1. Building Size

The equation using volume should be preferred, especially if one analyses the entire building. By analysing only sections of a building like the structural body, using items could be more efficient. The student sees volume as the overall more fitting alternative, as the embodied energy in one precast element is much higher than the embodied energy in a wooden plank. Thus, they should not be equally important to preserve in current state, understanding that this is not true for all types of materials. $A_d = \frac{V_r}{S*V_t}$ is therefore preferred and used going forward in this chapter. The building size is also accounted for, as the outcome of $\frac{V_r}{V_t}$ alone does not separate a doghouse from a skyscraper. The options *large*, *moderate*, and *small* are chosen, with a belonging Likert-scale numerical value, see table 8.1. No range of m^2 or m^3 towards size are given with the reason that a "typically average building size" is geographically dependent, e.g. Aalborg versus Manhattan.

The student suggests using the following BIM-based step-wise approach determining V_r and V_t using Honic [2019] scheme in figure 3.9 for a BIM-based MP (for precast elements):

1. Based on the original project material, the structural sections of the building are modelled on a *component* level.
2. An additional property of yes/or no for repetitiveness is added to the components, where repetitiveness is determined by e.g. a SE.
3. Data for both V_r and V_t can from there be quantified from the modelling software/viewer, e.g. ArchiCAD or Solibri.
4. The parameter architectural style and design A_d can now be calculated from retrieved data.

Note that this requires original project material. The student could not come up with a solution not involving original project material for determining V_r and V_t. Without its presence, the only way to determine the two variables to conduct *step one* (CQ1) and *step two* (CQ2) and by then you are more than halfway through mapping the building.

Number of similar buildings, Generic Estimate - B_g

The existence of similar buildings, meaning buildings with the same architectural style and design as the one in focus is highly important to maximise the frequency of repetitiveness and consistency. Say that one where finding the R-Score for one of the buildings in figure 8.4, one could estimate the existence of several similar buildings as high.

The parameter for similar buildings is B_g. A Likert-scale value is given in table 8.2, emphasising how generic the building in focus is compared to the rest of the building stock. Which value who will be chosen from table 8.2 should be concluded by people with a certain competency, see section 8.4.

Generic Estimation - B_g				
Extremely Generic 5	Very Generic 4	Moderately Generic 3	Slightly Generic 2	Not at all Generic 1

Table 8.2. Generic Estimation

8.2.2 Parameters Towards Material Bank Relevancy

The parameters presented here in section 8.2.2 seeks to find the most relevant buildings for urban mining besides repetitiveness. The parameters outlined for relevancy are:

1. Health Grade - C_h
2. Building Age - D_a
3. Accessibility Rate - E_a

Health Grade - C_h

A building´s condition/health is an important parameter when its material is questioned for reuse. The initial analysis in section 3.3.3 defines after Heinrich and Lang [2019] that RSL can indicate when a product or system needs to be recommissioned. Thus, influenced by the RSL, the building´s health grade is outlined as a parameter. Information on a building´s current condition before conducting any physical investigations (*step one*) could be collected by investigating design codes and records of facility management/maintenance. Table 3.6 in the initial analysis reflects upon reasons for weaknesses in strength, quality, and durability, where some of these reasons could be identified with the design codes. This, together with records from facility management/maintenance, a Likert-scale health grade can be determined by a competent specialist, see table 8.3. Some components in a building decline faster than others independent of maintenance. It should, therefore, be a matter of prioritization that if a component with a high embodied energy is in great condition with a long RSL, while another component with a low embodied energy is in a poor condition, the health grade should still be high. Such comparisons between components should of course comprehend the entire building, making an overall judgement for the building.

Health Grade - C_h				
Extremely good condition 5	Very good condition 4	Moderately condition 3	Slightly good condition 2	Not at all in good condition 1

Table 8.3. Health Grade

Building Age - D_a

A building´s age narrates a lot about the building. The older a building gets, the need for rehabilitation and/or probability for deconstruction/demolition usually increases. Thus, the building age is one of three parameters towards relevancy and the value is given in years since completion.

Accessibility Rate - E_a

Relevancy is also connected to the building´s *accessibility* - to what degree is the building ready for deconstruction, rehabilitation, or demolition. Obviously, one cannot just start to tear/deconstruct people´s houses and at the same time, it would be unwise to deconstruct a profitable already eco-friendly building with the reason that the material is needed in another construction project. Therefore, the accessibility rate investigates to what degree the building´s current function is sustainable from a monetary- and eco-perspective.

The building´s *accessibility rate* should be determined with an LCC, that has the purpose of collecting information such as lifespans and durability, the cost for maintenance, potential income on re-use scenarios, see table 3.4. Such an analysis should indicate what the future holds for a building, questioning the building´s sustainability. Evaluating building´s accessibility-grade should also include fractions of an MFA/LCA where the building´s energy consumption is compared towards salvageable- (embodied energy) and recyclable material, see chapter 10 *Further Research.* From there, a qualified person, see section 8.4, decides a Likert-scale score for the accessibility rate, see table 8.4.

Accessibility Rate - E_a				
Extremely sustainable 1	Very sustainable 2	Moderately sustainable 3	Slightly sustainable 4	Not at all sustainable 5

Table 8.4. Accessibility Rate

8.3 Repetitive and Relevancy Component Analysis and Material Passports →Template for Identification

Dependent on database-solution (how the MP-data is disseminated and stored), the student proposes the R-Score as an additional "data-tag"/property independent of the four branches of BAMB´s best practice MP, see figure 8.5. Alternatively the R-Score could be placed under process, as the RCA is intended as a process towards MPs for existing buildings. Section 3.2 described how a MP *'may serve for a single material, product(s), and entire system(s).* The R-Score hierarchical belongs at the system-level. Within the MP-database (material bank), one can now query out potential buildings with the R-Score displayed, making the material bank also a "bank over potential material banks".

The R-Score integrated within the MP instead as being an external affair has its intent. The proposed RCA and MP shares several data-assembling techniques e.g. LCC and some of the data required in Heinrich and Lang [2019]´s is already collected through the RCA and most of the information and data is recognizable as system-info. Thus, this "unfinished" MP will serve as the template for identifying the "next building".

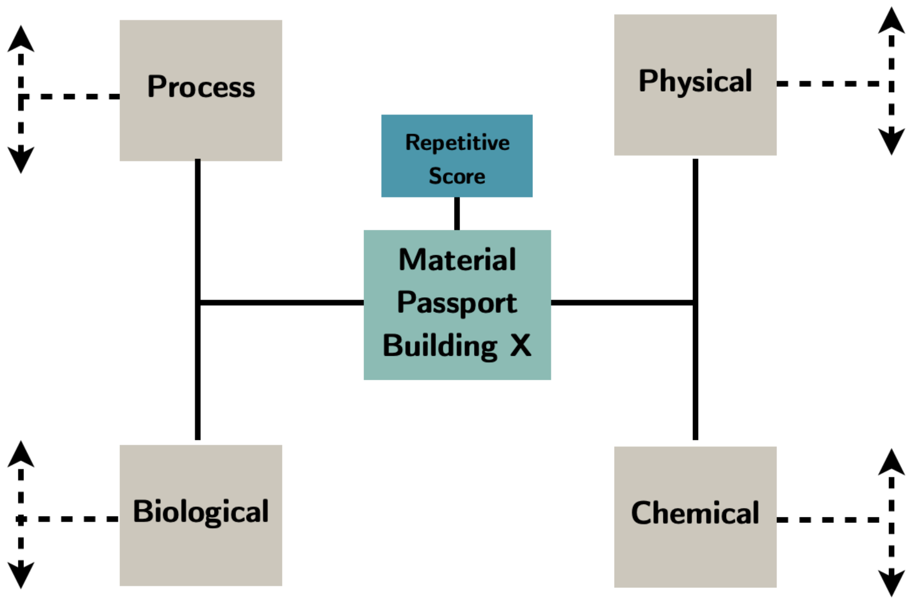

Figure 8.5. The R-Score within MP, adopted figure from the initial analysis, see figure 3.3.1

8.4 Competency

As mentioned in section 8.2.2 and 8.2.1, there is a need for certain competencies to complete an RCA. This suggested solution needs both engineers and architects since some of the parameters require a certain understatement, prerequisite knowledge, and experience to convert data into information.

8.5 *Repetitive and Relevancy Component Analysis* for the Case Building

This section has the purpose of conducting an RCA for the case-building used in the survey. However, some information were left out/not created for the survey to minimize information pushed on respondents, minimizing respondent-time. Therefore, some new information (written in bold) are added along with the original information in the list below, for the purpose of conducting this RCA.

- Completed between 1960-1980
- 300 m^2 divided into two floors.
- Steel and concrete elements.
- **Completed in 1970**
- **Located in Aalborg, Denmark.**
- **Flat roof**

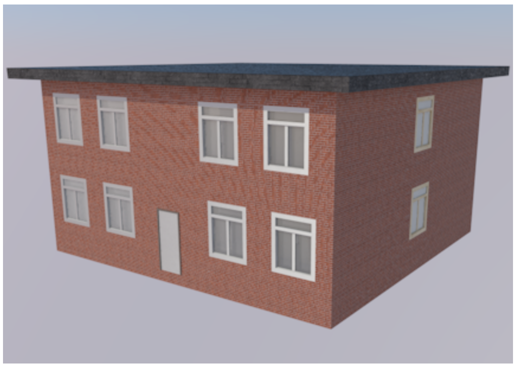
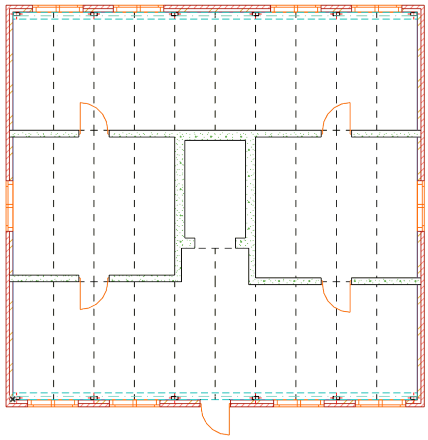

Figure 8.6. Case building´s floor plan and perspective, retrieved from ArchiCAD 23

8.5.1 Repetitive Parameters

Architectural style and design - A_d

Comparing the 300 m^2 building, 150 m^2 in footprint towards buildings in Aalborg city center, the case building is given a size-score *small* $\rightarrow S = 3$. The repetitive volume V_r (precast elements) is measured to 120.56 m^3 and total volume V_t of concrete 167.97 m^3, see table 8.5. Only precast elements are evaluated, hence the thesis framework and limitations.

A_d was given by

$$A_d = \frac{V_r}{S * V_t}$$

meaning

$$A_d = \frac{120.56\text{m}^3}{3 * 162.97\text{m}^3} = 0.25$$

Name	**Volume**	**Repetitive Volume**
Structural In Situ Concrete	42.41 m^3	No
Precast Concrete Elements	120.56 m^3	Yes
Total	162.97 m^3	120.56 m^3

Table 8.5. Volumes retrieved from ArchiCAD 23

Existence of similar buildings- B_g

The added information sets the location to Aalborg, Denmark. Figure 8.5 along with the information given at the beginning of this section, one can see and read that the case building consists of:

- Concrete precast elements.
- In situ cast concrete bearing interior walls.
- Brick facade.
- Flat roof.
- Elevator shaft as stiffening against horizontal forces.
- Building age →50 years.

Based upon these descriptions in architectural style and design, one could argue that in Aalborg, this is a somewhat generic building, and is therefore given the grade *moderately generic* $\rightarrow B_g = 3$.

If one with the righter competence and experience would analyse a real-life building, he/she should add more description along with original project material, design codes, etc. so the generic grade is better founded and determined upon design and style. For this example, the student´s intent is to illustrate the concept to determine the generic grade and therefore limit the descriptions and the procedure.

8.5.2 Relevancy-Parameters

Health Grade - C_h

Due to the building being fictive, the health grade is set to *Moderate* $\rightarrow C_h = 3$, see table 8.3. The student could have investigated design codes from 1970 and evaluate the design´s sustainability and quality since maintenance and facility management reports do not exist. However, the student does not possess the knowledge of an SE to evaluate the design ´s sustainability through a 50-year period and therefore the case building is given the neutral health grade from table 8.3.

Building Age - D_a

In the survey, the case building was said to be constructed between the 1960-80s. Being a fictive building, the student determines the case building completion year to 1970, meaning $D_a = 50$ (years).

Accessibility Rate - E_a

Table 8.6 shows some of the required data when performing an LCC, with the student´s estimated values for these towards the case building. The estimates are determined from table 8.5 and the information given on the case building. Based on these details, the building is given an accessibility rate *slightly sustainable* $\rightarrow E_a = 4$, see table 8.4. The LCC here is very limited, due to the purpose of illustrating an RCA.

LCC for the Case Building	
Manufacturing Cost	low
Cost for maintenance and operation	high
Cost for landfill, reuse	high
Potential income depending on re-use scenarios	high
Warranties	low

Table 8.6. LCC for the case building

8.5.3 Repetitive-score

The R-Score were given by the student´s suggested equation

$$R_s = A_d + \frac{\frac{B_c}{2} + 5E_a + 5B_g - 2C_h}{100}$$

meaning that

$$R_s = 0.25 + \frac{\frac{50}{2} + 5 * 4 + 5 * 3 - 2 * 3}{100}$$

$$R_s = 0.79$$

With the R-Score = 0.79, figure 8.7 shows that the case building has a yellow grade. The yellow grade is within the area of neutral, indicating one should map the building if no better alternatives exist.

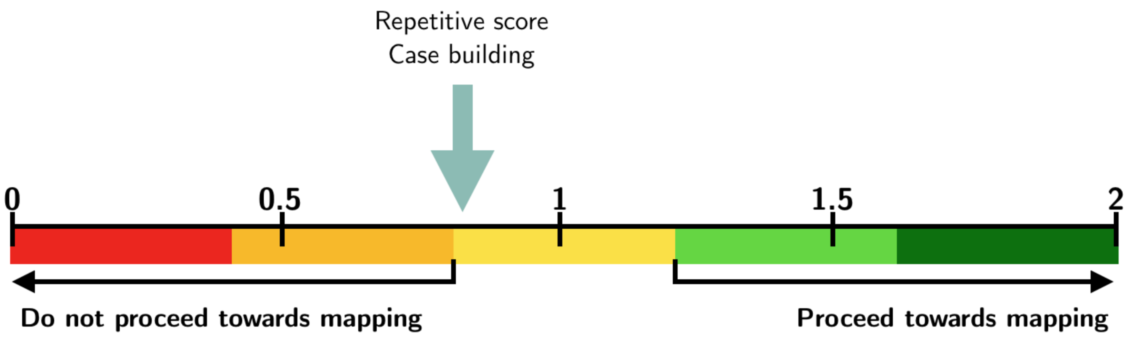

Figure 8.7. R-Score for the case building

9 Conclusion

The problem statement searched for ways to map existing buildings into material banks more efficient. The suggested solution through carefully chosen parameters allows mapping of existing buildings with homogeneous and repetitive patterns, and by doing so more efficient than "traditionally". However, this thesis found the presence of the existing project material highly important if the goal is to map existing building to a reasonable cost. Thus, the student concludes upon the thesis´s problem statement that *buildings can be mapped into material banks more efficiently by selectively choosing buildings that match criteria towards repetitiveness.* However, the repetitiveness can only be detected promptly with the use of original project material. Without its existence, mapping existing buildings as material banks will be costly.

Even if the original project material is unavailable, the importance of mapping buildings to initiate urban mining cannot be overstated. Existing buildings and urban mining is an inevitable part of the solution *today*, a solution towards net-zero energy construction projects and not only in futuristic scenarios. Every down-cycling of reusable materials is a loss towards sustainability, circular principles, and global climate goals, and still conducted often for a monetary win. Monetary obstacles should rather be seen as an incentive for a new marked and thus job creation.

10 | Further Research

10.1 Alternate for Original Project Material

This thesis concluded the importance of original project material. Since its existence is not always guaranteed, the students suggest further research involves searching for alternatives.

Backlogs, manufacturing orders with descriptions, manufacturing-specification (materials used, techniques, etc.) are information that if it exists, could help determine repetitiveness. In relation to concrete precast elements, manufacturers like *Consolis Spæncom* have been operating and producing concrete elements for seventy years [Spæncom.dk]. E.g. if a concrete manufacturer delivered a large of quanta with precast elements to apartment houses like the one illustrated in figure 8.4, they may possess information on how these were constructed. Such information could be an alternate for project material in terms of information upon the element´s material structure and by so helping the process towards existing buildings as material banks.

10.2 Energy Potential in the Repetitive and Relevancy Component Analysis

It was briefly mentioned in section 8.2.2 that there is a need for looking into the eco-perspective for a building when the accessibility rate is in question. Thus, an evaluation upon a building´s energy-consumption versus the material´s re-use potential needs to be accounted for before it is initiated for urban mining. This was found to comprehensive and somewhat out of the scope of this thesis. Therefore, the student suggest a comparison for further research, with annual energy consumption for a building on one side and embodied energy plus the outcome of down-cycled materials on the other side as, to enhance the preciseness of an RCA.

10.3 Repetitive-Detection

It was mentioned in section 8.2.1 that to calculate and determine the repetitive volume V_R, one could add a property in the preferred modelling tool that answers yes or no towards repetitiveness. The student suggests as further research to look for how to automate this process, by e.g. taking advantage of duplicate-finders like Solibri Model Checker.

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Appendix

A | Survey

Introduction (1 min)

This study is part of a master's thesis in Management in the Construction Industry, spring 2020 at Aalborg University. The survey´s intended duration is approx. 10 minutes, and all answers are anonymous. Suggested time spent on each of the survey´s pages is parenthesed in the headline.

The survey thematizes the reuse of building materials and examines how existing buildings can become a material bank for new buildings.

PREVIOUS NEXT

25%

EN DA NO

Background (1min)

Some quick questions about your background

Occupied in

-- Choose --

Work experience

- ○ 1-3 years
- ○ 3-10 years
- ○ 10+ years

Occupied in

- ○ Engineering Consultancy / Designer
- ○ Contractor

Describe your job title in terms of job description (structural engineer, geotechnical engineer etc.)

PREVIOUS NEXT 50%

EN DA NO

Prerequisite Knowledge (2min)

How familiar are you with the following terms?

Circular Economy

Not at all familiar | Slightly familiar | Somewhat familiar | Moderately familiar | Extremely familiar

Rehabilitation projects

Not at all familiar | Slightly familiar | Somewhat familiar | Moderately familiar | Extremely familiar

Material Passports (Information and data for a building, product or material)

Not at all familiar | Slightly familiar | Somewhat familiar | Moderately familiar | Extremely familiar

Environmental Product Declaration - EPD

Not at all familiar | Slightly familiar | Somewhat familiar | Moderately familiar | Extremely familiar

Life Cycle Analysis – LCA

Not at all familiar | Slightly familiar | Somewhat familiar | Moderately familiar | Extremely familiar

VDC with BIM-related processes.

Not at all familiar | Slightly familiar | Somewhat familiar | Moderately familiar | Extremely familiar

Concrete and precast production

Not at all familiar | Slightly familiar | Somewhat familiar | Moderately familiar | Extremely familiar

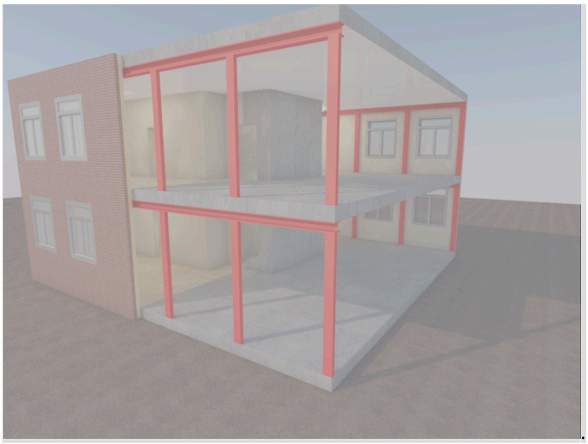
PREVIOUS NEXT

75%

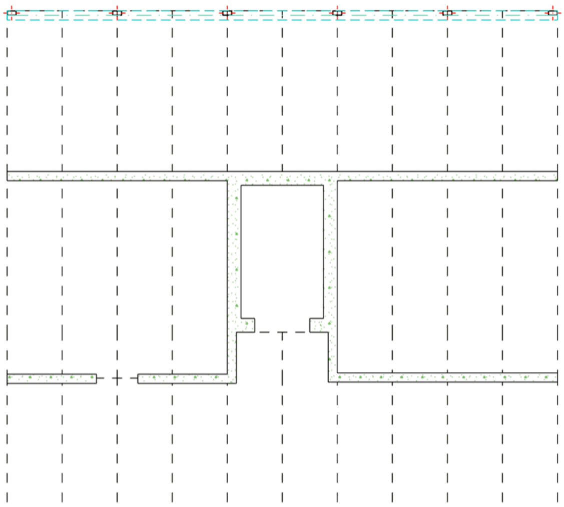
Case (6 min)

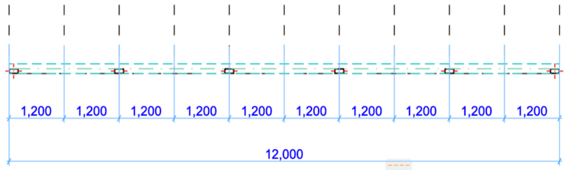
In the last part of the survey, you are asked to estimate resources (in hours) necessary for performing some larger operations connected to a “case-building”. Beneath each described operation you enter the number of hours you expect such operations require.

Beneath each operation, there is a slider where you are asked to describe your assumed complexity for the current operation, even though estimates for these operations will be relatively towards the individual solutions in different constructions.



The case-building is a two-story building with a 150 m2 footprint erected between 1960-1980, with a steel and concrete load-bearing structure. Prefabricated concrete elements have been used (except for the foundation) and the following operations are addressed towards these elements. The attached image and drawing intendeds to illustrate the scope of the building, but it does not show the entire structure. The building is a fully functional building, meaning the structure will not be “naked”





1. The first operation is to investigate and document the condition / "health" of all the prefabricated concrete elements in the case building. This would among other include inspection for damage, corrosion, scratches etc. as well as describe connections between the load-bearing systems in the case-building (e.g. between steel and concrete).

Amount of hours (one person)

Complexity

Very easy | Easy | Neutral | Complexed | Very complexed

---

2. The second operation is to calculate and determine design numbers (load capacity, type of concrete etc.) for the concrete elements and investigate and document reinforcement diameter, cover depth, volume, density etc. for the case building. The investigation should result into enough information you would find necessity for reusing the elements.

Amount of hours (one person)

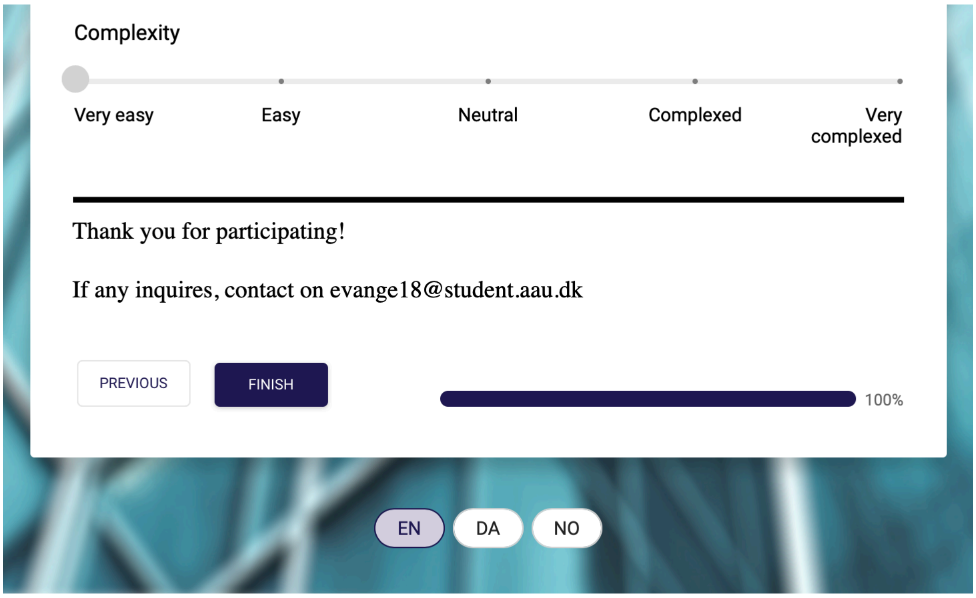
Complexity

Very easy | Easy | Neutral | Complexed | Very complexed

---

3. The third operation is to design a structural BIM-model of the case-building down to a detailed material level, meaning properties of the concrete element like compressive strengt, aggregate, reinforcement, dimensions etc. are described for each of the concrete element object in the model.

Amount of hours (one person)


Complexity
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If any inquires, contact on evange18@student.aau.dk
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1-3 years
10+ years
3-10 years
1-3 years
1-3 years
10+ years
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1-3 years
10+ years

Occupied in

Engineering Consultancy / Designer
Contractor
Contractor
Contractor
Contractor
Contractor
Contractor
Engineering Consultancy / Designer
Engineering Consultancy / Designer
Engineering Consultancy / Designer
Contractor
Engineering Consultancy / Designer
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Engineering Consultancy / Designer
Engineering Consultancy / Designer
Contractor
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Engineering Consultancy / Designer

Contractor

Engineering Consultancy / Designer

Engineering Consultancy / Designer

Engineering Consultancy / Designer

Contractor

Engineering Consultancy / Designer

Engineering Consultancy / Designer

Engineering Consultancy / Designer

Engineering Consultancy / Designer

Engineering Consultancy / Designer

Contractor

Engineering Consultancy / Designer

Engineering Consultancy / Designer

Engineering Consultancy / Designer

Engineering Consultancy / Designer

Engineering Consultancy / Designer

Describe your job title in terms of job description (structural engineer, geotechnical engineer etc.)

- Hydrauliker
- Prosjektingeniør
- Prosjektingeniør Kalkulasjon og Innkjøp
- Pi
- Formann Tømmer
- Prosjektleder
- Prosjektingeniør
- Bygningskonstruktør
- vegingeniør
- Konstruktør
- Prosjektingeniør Kalkulasjon og Innkjøp
- bygningskonstruktør
- Konstruktionsingeniør
- Konstruksjonsingeniør
- Konstruksjonsingeniør
- Konstruksjonsingeniør
- konstrukjonsingeniør
- konstruksjonsingeniør
- Prosjektingeniør
- Design manager
- BMS SPECIALIST
- El-ingeniør
- Konstruktionsingeniør
- VVS Ingeniør
- Project Manager
- konstruktionsingeniør
- Driftsrådgiver
- Structural Engineer
- Ingeniør
- Konstruktionsingeniør
- Bygningskonstruktør
- Konstruktionsingeniør
- projektleder
- Elektriske installationer

- Bygningskonstruktør
- Miljøingeniør
- konstruktionsingeniør på elementfabrik
- Konstruktionsingeniør
- Konstruktionsingeniør - projektering
- Konstruktionsingeniør
- Konstruktionsingeniør
- Bygningskonstruktør
- konstruktionsingeniør
- Konstruktionsingeniør
- Afdelingschef
- Områdedirektør
- konstruktionsingeniør
- Konstruktionsingeniør
- Afløbsteknik
- Konstruktionsingeniør
- Rådgiver Energi og Miljø

Circular Economy	Rehabilitation projects	Material Passports (Information and data for a building, product or material)	Environmental Product Declaration - EPD	Life Cycle Analysis – LCA	VDC with BIM-related processes.	Concrete and precast production
Not at all familiar	Slightly familiar	Slightly familiar	Not at all familiar	Not at all familiar	Slightly familiar	Slightly familiar
Slightly familiar	Somewhat familiar	Somewhat familiar	Slightly familiar	Slightly familiar	Slightly familiar	Somewhat familiar
Not at all familiar	Moderately familiar	Moderately familiar	Extremely familiar	Moderately familiar	Somewhat familiar	Moderately familiar
Somewhat familiar	Somewhat familiar	Moderately familiar	Slightly familiar	Slightly familiar	Somewhat familiar	Moderately familiar
Somewhat familiar	Extremely familiar	Slightly familiar	Moderately familiar	Somewhat familiar	Moderately familiar	Moderately familiar
Not at all familiar	Moderately familiar	Somewhat familiar	Slightly familiar	Extremely familiar	Slightly familiar	Moderately familiar
Slightly familiar	Somewhat familiar	Slightly familiar	Not at all familiar	Slightly familiar	Slightly familiar	Somewhat familiar
Somewhat familiar	Moderately familiar	Not at all familiar	Moderately familiar	Moderately familiar	Somewhat familiar	Somewhat familiar
Somewhat familiar	Moderately familiar	Not at all familiar	Somewhat familiar	Somewhat familiar	Moderately familiar	Moderately familiar
Slightly familiar	Somewhat familiar	Slightly familiar	Slightly familiar	Somewhat familiar	Slightly familiar	Somewhat familiar
Slightly familiar	Somewhat familiar	Not at all familiar	Not at all familiar	Slightly familiar	Somewhat familiar	Somewhat familiar
Not at all familiar	Moderately familiar	Slightly familiar	Slightly familiar	Not at all familiar	Slightly familiar	Moderately familiar
Moderately familiar	Moderately familiar	Slightly familiar	Somewhat familiar	Somewhat familiar	Not at all familiar	Moderately familiar
Not at all familiar	Somewhat familiar	Slightly familiar	Not at all familiar	Slightly familiar	Not at all familiar	Moderately familiar
Somewhat familiar	Somewhat familiar	Not at all familiar	Not at all familiar	Slightly familiar	Moderately familiar	Somewhat familiar
Not at all familiar	Somewhat familiar	Not at all familiar	Not at all familiar	Slightly familiar	Not at all familiar	Moderately familiar
Not at all familiar	Slightly familiar	Not at all familiar	Not at all familiar	Not at all familiar	Not at all familiar	Moderately familiar
Slightly familiar	Somewhat familiar	Not at all familiar	Slightly familiar	Slightly familiar	Slightly familiar	Somewhat familiar
Moderately familiar	Somewhat familiar	Slightly familiar	Slightly familiar	Somewhat familiar	Moderately familiar	Slightly familiar
Slightly familiar	Somewhat familiar	Slightly familiar	Slightly familiar	Slightly familiar	Slightly familiar	Slightly familiar
Somewhat familiar	Somewhat familiar	Slightly familiar	Slightly familiar	Slightly familiar	Somewhat familiar	Somewhat familiar
Slightly familiar	Moderately familiar	Slightly familiar	Slightly familiar	Somewhat familiar	Slightly familiar	Moderately familiar
Somewhat familiar	Slightly familiar	Not at all familiar	Somewhat familiar	Somewhat familiar	Not at all familiar	Slightly familiar
Somewhat familiar	Slightly familiar	Slightly familiar	Somewhat familiar	Somewhat familiar	Not at all familiar	Somewhat familiar
Slightly familiar	Moderately familiar	Somewhat familiar	Slightly familiar	Slightly familiar	Somewhat familiar	Moderately familiar
Slightly familiar	Moderately familiar	Not at all familiar	Not at all familiar	Slightly familiar	Slightly familiar	Slightly familiar
Not at all familiar	Not at all familiar	Not at all familiar	Not at all familiar	Not at all familiar	Not at all familiar	Extremely familiar
Slightly familiar	Slightly familiar	Not at all familiar	Not at all familiar	Slightly familiar	Not at all familiar	Extremely familiar
Somewhat familiar	Extremely familiar	Not at all familiar	Slightly familiar	Somewhat familiar	Not at all familiar	Extremely familiar

Slightly familiar	Somewhat familiar	Somewhat familiar	Slightly familiar	Somewhat familiar	Not at all familiar	Moderately familiar
Somewhat familiar	Moderately familiar	Moderately familiar	Slightly familiar	Slightly familiar	Slightly familiar	Somewhat familiar
Somewhat familiar	Somewhat familiar	Slightly familiar	Slightly familiar	Slightly familiar	Slightly familiar	Somewhat familiar
Somewhat familiar	Moderately familiar	Slightly familiar	Not at all familiar	Slightly familiar	Not at all familiar	Moderately familiar
Extremely familiar	Extremely familiar	Moderately familiar	Moderately familiar	Somewhat familiar	Slightly familiar	Somewhat familiar
Slightly familiar	Slightly familiar	Not at all familiar	Not at all familiar	Not at all familiar	Slightly familiar	Moderately familiar
Slightly familiar	Moderately familiar	Slightly familiar	Slightly familiar	Somewhat familiar	Slightly familiar	Extremely familiar
Not at all familiar	Moderately familiar	Not at all familiar	Not at all familiar	Slightly familiar	Not at all familiar	Moderately familiar
Slightly familiar	Somewhat familiar	Slightly familiar	Slightly familiar	Slightly familiar	Slightly familiar	Extremely familiar
Slightly familiar	Slightly familiar	Not at all familiar	Not at all familiar	Not at all familiar	Not at all familiar	Moderately familiar
Not at all familiar	Somewhat familiar	Not at all familiar	Not at all familiar	Somewhat familiar	Slightly familiar	Extremely familiar
Slightly familiar	Somewhat familiar	Not at all familiar	Slightly familiar	Slightly familiar	Not at all familiar	Somewhat familiar
Somewhat familiar	Moderately familiar	Not at all familiar	Not at all familiar	Somewhat familiar	Slightly familiar	Somewhat familiar
Somewhat familiar	Moderately familiar	Slightly familiar	Not at all familiar	Slightly familiar	Somewhat familiar	Moderately familiar
Not at all familiar	Slightly familiar	Somewhat familiar	Not at all familiar	Slightly familiar	Not at all familiar	Extremely familiar
Moderately familiar	Moderately familiar	Not at all familiar	Not at all familiar	Slightly familiar	Somewhat familiar	Moderately familiar
Slightly familiar	Moderately familiar	Somewhat familiar	Slightly familiar	Slightly familiar	Slightly familiar	Moderately familiar
Not at all familiar	Somewhat familiar	Not at all familiar	Not at all familiar	Slightly familiar	Not at all familiar	Somewhat familiar
Moderately familiar	Moderately familiar	Not at all familiar	Moderately familiar	Moderately familiar	Not at all familiar	Moderately familiar

1. The first operation is to investigate and document the condition / "health" of all the prefabricated concrete elements in the case building. This would among other include inspection for damage, corrosion, scratches etc. as well as describe connections between the load-bearing systems in the case-building (e.g. between steel and concrete). - Amount of hours (one person)
7.50
3.00
28.00
15.00
30.00
75.00
15.00
15.00
5.00
100.00
20.00
25.00
70.00
160.00
20.00
8.00
10.00
30.00
5.00
20.00
14.00
37.00
40.00
8.00
25.00
10.00

1.00

20.00

8.00

15.00

50.00

37.00

5.00

Complexity
Neutral
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Easy
Very easy
Neutral
Very complexed
Easy
Neutral

2. The second operation is to calculate and determine design numbers (load capacity, type of concrete etc.) for the concrete elements and investigate and document reinforcement diameter, cover depth, volume, density etc. for the case building. The investigation should result into enough information you would find necessity for reusing the elements. - Amount of hours (one person)
15.00
16.00

22.00
40.00
15.00
37.50
25.00
60.00
40.00
250.00
100.00
90.00
90.00
160.00
20.00
45.00
30.00
200.00
21.00
40.00
74.00
200.00
70.00
5.00
37.00
40.00
2.00
75.00
4.00
15.00
100.00
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Complexity
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3. The third operation is to design a structural BIM-model of the case-building down to a detailed material level, meaning properties of the concrete element like compressive strengt, aggregate, reinforcement, dimensions etc. are described for each of the concrete element object in the model. - Amount of hours (one person)

23.00
40.00
22.00
60.00
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37.50
37.00
50.00
40.00
450.00
20.00
45.00
50.00
100.00
20.00
15.00
10.00
150.00
24.00
40.00
111.00
200.00
100.00
20.00
37.00
40.00

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5.00
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Complexity

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Language

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E-mail

Overall Status
Partially Complete
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Partially Complete
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Distributed